โมดูลัสคืนตัวและปัจจัยที่มีอิทธิพลของมวลรวมหินปูนแบบไม่เชื่อมแน่น

นายจันเพ็ง พรมมาวอน

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาวิศวกรรมโยธา ภาควิชาวิศวกรรมโยธา
คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2555

RESILIENT MODULUS AND INFLUENCING PARAMETERS OF UNBOUND CRUSHED LIMESTONE

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A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Civil Engineering
Department of Civil Engineering
Faculty of [Engineering]
Chulalongkorn University
Academic Year 2012

Thesis Title	RESILIENT MODULUS AND INFLUENCING PARAMETERS OF UNBOUND CRUSHED LIMESTONE
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Field of Study	Civil Engineering
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จันเพ็ง พรมมาวอน : โมดูลัสคืนตัวและปัจจัยที่มีอิทธิพลของมวลรวมหินปูนแบบไม่เชื่อมแน่น. (RESILIENT MODULUS AND INFLUENCING PARAMETERS OF UNBOUND CRUSHED LIMESTONE) อ. ที่ปรึกษาวิทยานิพนธ์หลัก: ผศ.ดร. บุญชัย แสงเพชรงาม, 113 หน้า.

วิธีการออกแบบถนนกำลังจะพัฒนาไปสู่การออกแบบโดยวิธีกลศาสตร์-ประสบการณ์ ซึ่งการออกแบบโดยวิธีเชิงกลศาสตร์-ประสบการณ์จะมีข้อดีมากกว่าการออกแบบเชิงประสบการณ์ แต่สิ่งสำคัญที่จะสามารถใช้วิธีเชิงกลศาสตร์ประสบการณ์ได้จะต้องรู้ถึงลักษณะความเสียหายของโครงสร้างชั้นทาง ซึ่งสามารถทำได้โดยการศึกษาพฤติกรรมของถนนภายใต้น้ำหนักบรรทุกแบบกระทำซ้ำ ในงานวิจัยนี้ใช้หินปูน 2 ขนาดคละในการหาค่าโมดูลัสคืนตัว โดยใช้เครื่องทดสอบแบบสามแกนให้แรงกระทำซ้ำ ทดสอบอ้างอิงตามมาตรฐาน AASHTO T307 ซึ่งค่าโมดูลัสคืนตัวจะขึ้นอยู่กับระดับของแรงกระทำ และปริมาณน้ำในวัสดุจะส่งผลอย่างมีนัยสำคัญ ผลการทดลองจะสะท้อนพฤติกรรมของถนนด้านค่าโมดูลัสคืนตัวของวัสดุพื้นทางแบบไม่เชื่อมแน่น เพื่อใช้ในการออกแบบโดยวิธีกลศาสตร์-ประสบการณ์

ภาควิชา วิศวกรรมโยธา ลายมือชื่อนิสิต
สาขาวิชา วิศวกรรมโยธา ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก
ปีการศึกษา 2555

5370677021 : MAJOR CIVIL ENGINEERING

KEYWORDS : UNBOUND GRANULAR MATERIALS, MECHANISIC-EMPIRICAL PAVEMENT DESIGN, REPEATED LOAD TRIAXIAL TEST

CHANPHENG PHOMMAVONE: RESILIENT MODULUS AND INFLUENCING PARAMETERS OF UNBOUND CRUSHED LIMESTONE.
ADVISOR: ASST. PROF. BOONCHAI SANGPETNGAM, Ph.D., 113 pp.

The design method of pavement structure is evolving to the new Mechanistic-Empirical (M-E) approach. The M-E approach has many significant benefits over the empirical design approach. One major success is it can identify the distress patterns and the progress rate at a given pavement structure. This is possible by the knowledge of mechanistic behavior of pavement materials responding to the repeated loads. In order to obtain mechanistic properties of the road base materials for the M-E approach, a set of laboratory experiment needed to be conducted on the materials. In this research, two gradation of unbound crushed limestone are selected to determine the resilient modulus using the repeated-load triaxial test according to AASHTO T307. The resilient modulus value is dependent on the stress state. And the water content plays significantly to the resilient modulus. The results of these tests provide the resilient modulus characteristic of unbound granular based materials for using in the Mechanistic-Empirical Pavement Design.

Department : Civil Engineering
Field of Study : Civil Engineering
Academic Year : 2012

Student's Signature
Advisor's Signature

ACKNOWLEDGEMENTS

I would like to express sincere gratitude to my advisor, Assistant Professor Boonchai Sangpetngam for helpful suggestion, his time, kindness and continuous support throughout this research and study.

Sincere appreciation to dissertation committee member Assoc.Prof. Kasem Choocharukul, chairman of committee, Asst.Prof. Withit Pansuk, thesis committee member, and Dr. Auckpath Sawangsuriya, thesis external examiner from Bureau of Road Research and Development, Department of Highway.

I would like to thank all teachers of the Transportation Engineering Division, students and classmate as well.

I would like to acknowledge the Department of Highways of Thailand for the supporting equipment for this research, the AUN/SEED-Net for the research fund, the Infrastructure Management Research Unit under the Ratchadaphiseksomphot Fund, and the Stimulus Package 2 (SP2) of Ministry of Education under the theme of Green Engineering for Green Society for the collaboration and academic support.

Specially, I am grateful to my family and my mother, for their invaluable moral support.

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CHAPTER I

INTRODUCTION

1.1 Background

Currently the pavement design method is evolving to the new Mechanistic-Empirical (M-E) approach. The M-E approach has many significant benefits over the empirical design approach. One major success is it can estimate the stresses and strains in the pavement layers and correlate those values to identify the distress patterns and the progress rate at a given pavement structure. This is possible by the knowledge of mechanistic behavior of pavement materials responding to the repeated loads. In order to obtain stresses and strains of the road base layer, the key mechanistic parameter i.e. the resilient modulus of the base material must be known. At present, it is possible to determine the resilient modulus of the base material by conducting a set of laboratory test using the repeated load triaxial test system.

1.2 Objectives

The main objective of this research is to study influences of the key parameters: gradation, water content and compaction level on the resilient modulus of the selected unbound granular material.

1.3 Scope of Research

In this study, the limestone from a local source is used in representing the unbound granular material typically for base course construction in Thailand. The mechanistic empirical characteristics of the unbound granular material that are focused in this study are resilient modulus under cyclic loads. The resilient modulus may be significantly influenced by the following variables mostly found in one job site condition:

grain size distribution; moisture content; compacted density level. The crushed limestone from Saraburi province is used in this study as a representative granular base material for its popularity in Thailand.

1.4 Brief Methodology

This is a case study which includes the literature reviews, experimental design method tested, state data analysis and conclusion. This study particularly focused on the factor effected parameter to resilient modulus of UGM. The research would be done step by step as shown below:

- Review the pertinent literature of Resilient Modulus (M_r), M_r testing method and its importance of M_r Characterization including moisture saturation, level compaction for controlling dry density, modulus nonlinearity in soils and possible laboratory testing methods, influencing factors and its importance in UGM determination, and analysis method tested. All the available sources are text books, journals, and international conference papers. They are all data can to be searched from pasted studies, internet websites, online libraries, and electronic database. All of involved literature reviews are entirely exhibit in Chapter 2.
- Type of material selected for testing and its properties are exhibit in Chapter 3. A detailed explanation about specimen preparation methods, and specimen conducted testing, is also given in chapter three.
- Results and analysis are presented in Chapter 4.
- Conclusions, recommendation, limitation of study, and further study are in the Chapter 5.

1.5 Benefits

1. Obtain the key mechanistic parameters of a local unbound granular base material for using in the Mechanistic-Empirical pavement design method.
2. Obtain statistical relationships between the mechanistic parameters and the significant variables of the local unbound granular base material.

CHAPTER II

LITERATURE REVIEW

2.1 Mechanistic-Empirical Pavement Design

2.1.1 Overview

The Mechanistic-empirical (M-E) pavement design approach has been developed to update the conventional pavement design method which is solely based on empirical observations of pavement condition under various traffic loads and surroundings. The main objective of M-E design method is to identify pavement responses to load (stresses and strains) and use the observed pavement performance to establish relationships. As the name of this approach suggests, there are two important elements which define the M-E pavement design approach, namely “mechanistic part” and “empirical part”. The “mechanistic part” makes use of engineering mechanics application to evaluate pavement responses (stresses and strains) when subjected to vehicular loads while the “empirical part” which is usually presented in an equation setup known as “distress transfer model” associates the mechanistic responses to the pavement distresses.

There are many advantages of the M-E design approach over the conventional design method. The primary benefits of M-E design approach are:

i. It can be used for new construction as well as pavement rehabilitation.
ii. It provides better representation of the loading conditions.
iii. It makes realistic prediction of specific type of distress (fatigue cracking, transverse cracking, rutting etc.)
iv. It is efficient in utilizing available materials.
v. It incorporates seasonal and aging effects on materials.

vi. It provides room to extrapolate from limited amounts of field or laboratory data before attempting important projects, saving money and time in the process.

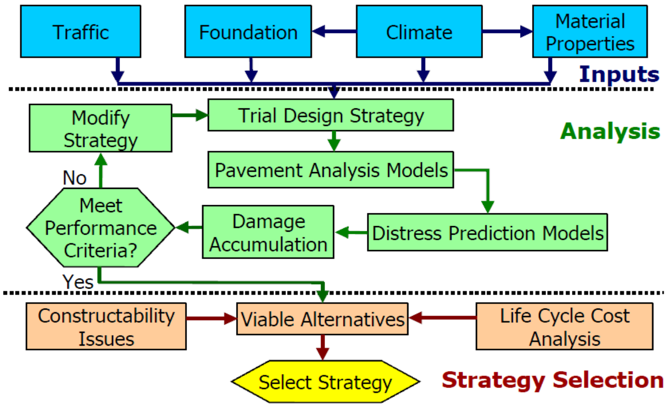


Figure 2.1 Mechanistic-Empirical Design Framework (NCHRP, 2004)

2.1.2 Pavement material characterization

A large set of material input is a distinctive property of the M-E design approach over the AASHTO flexible pavement design procedure. These material inputs may be categorized in one of the three major groups namely pavement response model material inputs, material-related properties, and climatic model material inputs. Temperature and moisture, being significant climatic inputs for pavement design, climatic-related material properties are used to determine variations due to temperature and moisture within the pavement structure. The pavement response model material input helps to determine the nature of distress at critical points within the pavement structure when subjected to vehicular loads and temperature differences. These structural responses are ultimately used by the distress models along with complimentary material properties to predict pavement performance.

2.2 Mechanical Behaviors of Unbound Granular Materials Under Repeated Load

2.2.1 Stress-strain behavior under traffic loads

The stresses acting on a loaded material body is characterized by a stress element comprising of a normal and shear stress component (Figure 2.2). When all stresses components are present (not zero), it has been proved that three perpendicular planes exist on which the shear stresses are zero. This implies that stresses on these planes are represented by a set of three normal stresses also called as principal stresses σ_1, σ_2 and σ_3 (Figure 2.2)

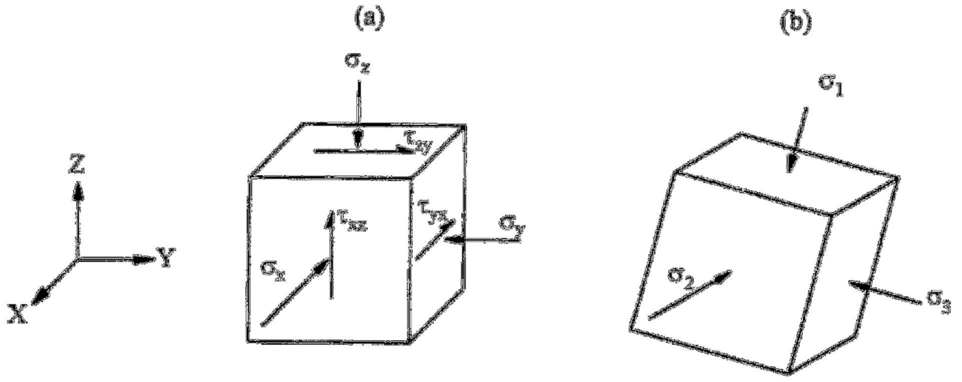


Figure 2.2 Stress components acting on an element (Lekarp, 1997)

The principal stresses (σ_1, σ_2, σ_3) are physical invariants meaning that they are unaffected by transformation of coordinates. The pavement structure in the field is subjected to wheel loads coming from vehicular traffic and due to this nature of the loading, the unbound granular material (UGM) layer is exposed to varying magnitudes of vertical, horizontal and shear stresses. Consequently, rotation of the principal stress occurs. Figure 2.3 shows that the principal stresses act vertically and horizontally only when the shear stresses are zero, i.e. directly beneath the center of the wheel load.

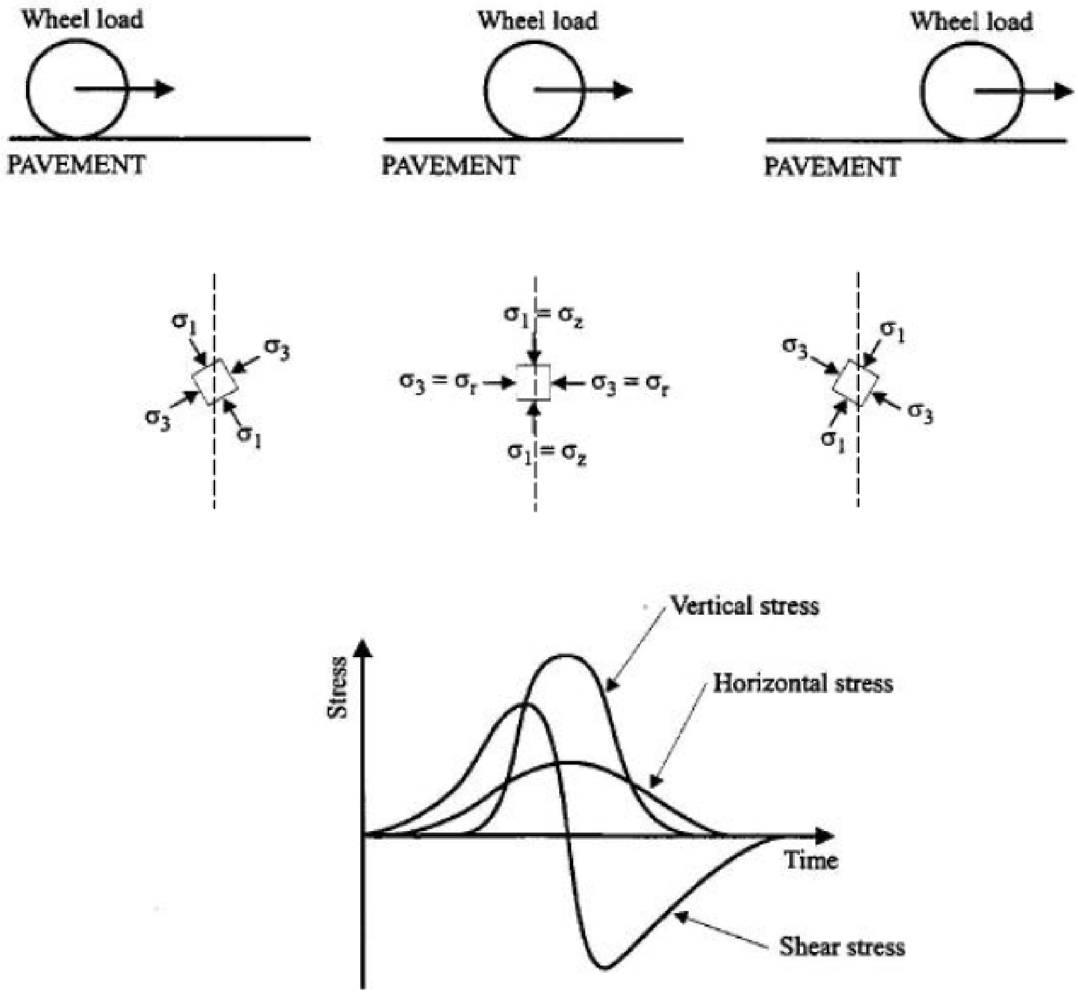


Figure 2.3 Stresses under a rolling wheel load (Lekarp and Dawson, 1998)

Repeated load triaxial (RLT) test is the most commonly used method for UGM characterization. In a RLT test, combinations of vertical and horizontal stresses can be reproduced. But this type of loading does not allow for the rotation of the principal stresses with exceptions to some new RLT equipment which incorporates simulation techniques. The level of applied stresses in a RLT test is in par with the in-situ principal stresses directly beneath the center of the wheel. If the in situ stress condition below the center of a single wheel load is considered, then $\sigma_1 = \sigma_z$ = vertical stress, and $\sigma_2 = \sigma_3 = \sigma_r$ = horizontal stress (Lekarp and Dawson, 1998).

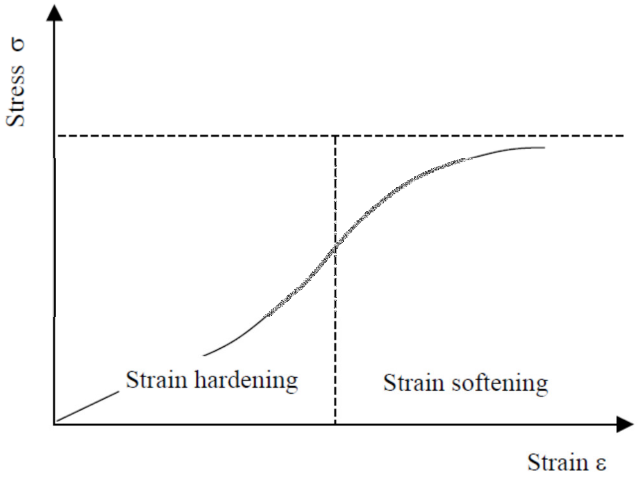


Figure 2.4 Stress-strain behaviors of UGMs (Lekarp and Dawson, 1998)

A study on the deformation characteristics of UGM have found that the deformation response can be classified as recoverable (resilient) deformation and residual (permanent) deformation both of which depends on the applied stress (Lekarp and Dawson, 1998). Therefore, the dynamic deformation response is controlled by the stress-strain behavior of the material. Figure 2.4 shows a typical stress-strain relation i.e. as the stress increase, the material's resistance to further strain reduces. At low stress intensity, the stiffness of the material increases with the increase in load (strain hardening). As a result of strain hardening, UGM particles undergo rearrangement and gets closer. Further increasing the stress (near to failure), brings about a decrease in the stiffness of the material (strain softening). Eventually the material will fail.

UGM are quite different from soils in their response to applied cyclic loads. UGMs are continuously graded granular materials, consisting in general of crushed rocks or crushed natural gravels. These materials carry only small amount of tensile stress. UGMs in a pavement structure are exposed to numerous loadings during its service life. The resilient deformation recovers after each load cycle whereas the permanent deformation gets accumulated. The resilient and permanent deformations can arise even at small stresses. The stress-strain behavior for UGMs is given by a non-linear curve which is further characterized by the formation of a hysteresis loop that occurs when subjected to stresses during each load cycle. The resilient and permanent strain can be evaluated at the hysteresis loop for the each load cycle.

2.2.2 Repeated loading behaviors

Even though granular materials are not elastic yet it undergoes some permanent deformation after each load application. After the first few load applications, the increase in permanent deformation is much smaller than the increase in resilient (recoverable) deformation. If the applied load is less than the strength of the material, continuous loading results in deformations that are almost completely recoverable and proportional to the load and therefore can be considered elastic. Resilient Modulus (M_r) is a fundamental material property used to characterize this behavior of unbound pavement materials. The term ‘resilient’ has a specific meaning. It refers to that portion of the energy that is put into a material upon loading and recovered while unloading. The rest of the energy that is not recovered results in the accumulation of strain in the material and ultimately cause rutting. Figure 2.5 shows basic strains in granular materials during each load cycle.

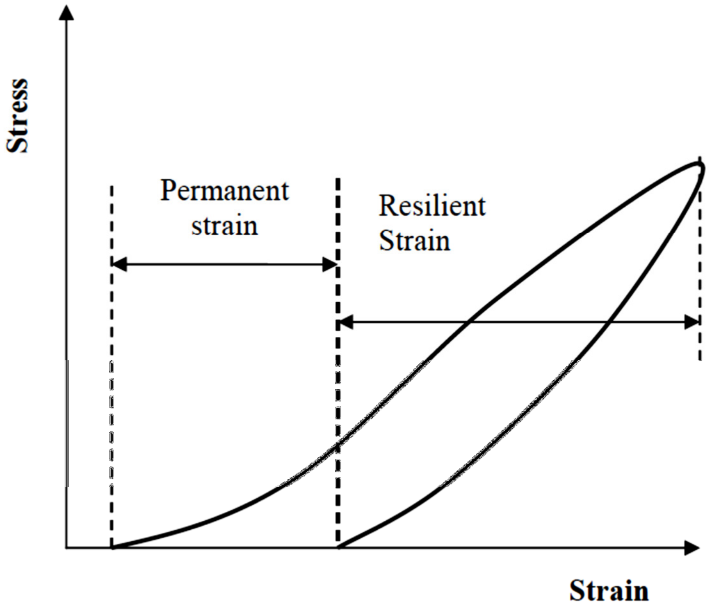


Figure 2.5 Basic strains in granular materials during each load cycle

Researchers have concluded that under repeated loading, UGM properties like resilient modulus and permanent deformation are major factors influencing the structural performance. RLT test is used to determine these material properties. The test applies repeated axial loads on a cylindrical specimen followed by a confining pressure from the tri-axial pressure chamber. Deformation responses are then recorded and used to calculate the resilient modulus and permanent deformation.

2.2.3 Resilient modulus

The Resilient Modulus (M_r) is the most commonly used parameter that describes subgrade material stiffness. It is a measure of the degree to which a material can recover from stress levels induced by the traffic loads. Actually, M_r is the elastic modulus based on the recoverable strain under repeated loads .The resilient modulus is known to be nonlinear and stress dependent. For RLT tests with constant confining stress, the resilient modulus is defined as the ratio of the peak axial repeated deviator stress to the peak recoverable axial strain of the specimen.

$$\mathrm{M_r} = \frac{(\sigma_1 - \sigma_3)}{\varepsilon_1} = \frac{\sigma_\mathrm{d}}{\varepsilon_\mathrm{d}^\mathrm{r}} \qquad \text{(Eq 2.1)}$$

Where:

M_r = resilient modulus,

σ_1 = major principal or axial stress,

σ_3= minor principal or confining stress,

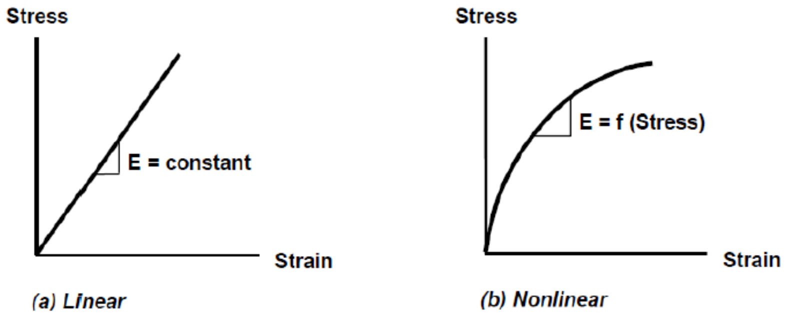
σ_d = deviator stress,

ε_1 = major principal or axial resilient strain, and

ε_a^r= axial resilient strain.

2.2.4 Nonlinear resilient modulus model

UGMs and asphalt concrete at high temperatures are best demonstrated by a stress-dependent model. Figure 2.6 shows linear and nonlinear material behavior. It is clear from the figure that linear behavior has a constant modulus while nonlinear behavior has stress-dependent modulus. UGMs exhibit nonlinear trend and are best characterized with a stress-dependent model. The MEPDG uses the resilient modulus to determine the stiffness for the unbound layers in a pavement structure. The generalized model in MEPDG for calculations of resilient modulus of stress-dependent material is shown by equation 2.2



(a) Linear

(b) Nonlinear

Figure 2.6 Linear and Nonlinear Material Behavior (NCHRP, 2004)

$$M_r = k_1 p_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3} \qquad \text{(Eq 2.2)}$$

Where:

M_r = resilient modulus. Psi

θ = bulk stress $= \sigma_1 + \sigma_2 + \sigma_3$

σ_1 = major principal stress

σ_2 = intermediate principal stress

= σ_3 for Mr Test on cylindrical specimen

σ_3 = minor principal stress/confining pressure

τ_{oct} = octahedral shear stress

P_a = normalizing stress

k_1, k_2, k_3 = regression constant

The octahedral shear stress is determined by:

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2} \quad \text{(Eq 2.3)}$$

2.2.5 Determination of Resilient Modulus

The standard procedure used for resilient modulus determination is AASHTO T307-99 (2007): “Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials”. The stress states and confining pressures are shown in figure 2.7

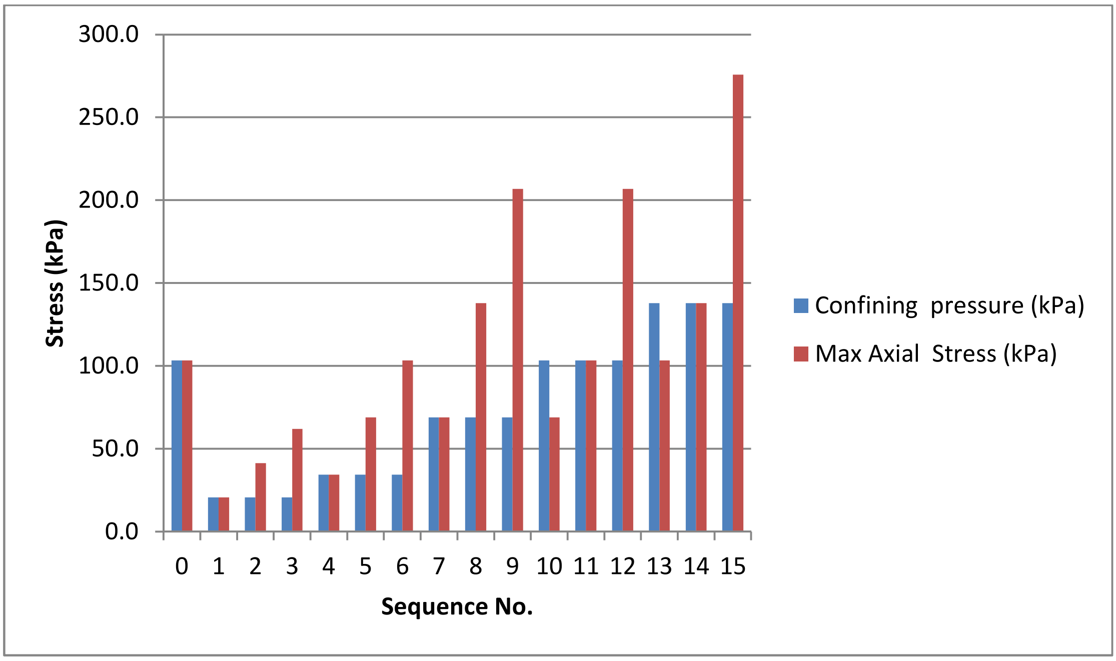


Figure 2.7 Loading stress and confining stress on each testing sequence

In the MEPDG, the resilient modulus test results are used to determine the regression constants (k_1, k_2, k_3). From equation 2.2, the linear and nonlinear regression analyses are used to fit the model. The coefficients will be the input in the Design Guide software.

2.3 Relevant Research Studies

Jeong Ho Oh et,al (2011) said that the correction factors (CFs) for determining equivalent laboratory resilient modulus (MR) values, acquired the corresponding unbound granular layer modulus from in situ pavement testing to support the flexible pavement design based on mechanistic-empirical pavement design guide (M-EPDG). To evaluate CFs for lime rock base, mechanically stabilized subgrade, and embankment materials, he said conducting field and laboratory test programmer along with reviewing available data. He compared field modulus determined from back calculation of falling weight deflector meter (FWD) data and laboratory determined modulus that considers in situ moisture content condition based on soil–water characteristic curve. The once he said that the fitted curve based on the calculated FWD load included stress be consider for converting FWD back calculated modulus to equivalent laboratory resilient modulus for design based on the MEPDG.

Mohamed Attia (2011) the studies found that the determination of the elastic modulus of pavement material is vital for any mechanistically based design and analysis. The resilient modulus was measured for samples containing different ratios of RAP. RAP material had higher MR than typical base aggregate. RAP blends were less sensitive to bulk stress and more sensitive to confining pressure compared to base aggregate. Tam and brown model which relates the MR to (P/1d) had no ability to predict the resilient modulus of RAP.

PeijunGuo et al (2010) to studies found that the influence of strain level on the resilient modulus of unbound granular materials is significant. The resilient modulus may be 40% higher than that obtained from standard resilient modulus testing when relative amplitudes of cyclic and static axial stress were changed. And the resilient modulus may not be uniquely determined from the bulk stress and the total deviator stress, The strain level dependency on resilient modulus can be reasonably described by a hyperbolic model.

Magnusdottir and Erlingsson (2002) studied resilient modulus or stiffness of unbound granular base course materials by using repeated load triaxial testing (RLTT). It was discovered that the material stiffness clearly increased when the compaction level increased. As the compaction effort was increased and the stiffness increased. Moisture also influenced the stiffness behavior. As the water content increased, stiffness increased. This was true when the degree of saturation was well below full saturation. But as the water content increased close to the full saturation, stiffness decreased, in some cases a total collapse were observed during the testing process.

Guo and Emery (2011) said that the influence of strain level on the resilient modulus of unbound granular materials is significant. The resilient modulus may be 40% higher than acquired from standard resilient modulus testing when relative amplitudes of cyclic and static axial stress were changed. And the resilient modulus may not be uniquely determined from the bulk stress and the total deviator stress.

Ekblad and Isacsson (2011) said that increased water content causes reduction in resilient modulus and increase in Poisson ratio. This behavior is more pronounced as the grading parameter is decreased. The large increase in Poisson ratio is to some extent in contrast to previous reports.

Ba et al. (2011) conducted a number of resilient modulus tests on local materials and revealed that the resilient modulus was significantly affected by the water content for the Limestone and less affected by water content for black quartzite, the red quartzite and the basalt tested. Specimens compacted with different density showed that the resilient modulus increases around 25% for relative density ranging from 77% to 119% and the variation was more significant at high stress states than at low stress states

Hani H. Titi et (2011) study about determined for Mr value for typical plastic soil propertied Mr to correlation parameter k constant to prediction by ME equation for finding of k from the physic propertied of soil.

CHAPTER III

RESEARCH METHODOLOGY

3.1 Introduction

In this chapter, the research methodology used in the testing program will be discussed. The crushed limestone used in this study was collected from Saraburi province. This material is a representative of the unbound granular material which be used as base and subbase layer in flexible pavement construction. The test methods refer to many international test standards such as American Society for Testing and Materials (ASTM), American Association of State Highway and Transportation Officials (AASHTO) and European Standard (EN)

3.2 Material

The crushed limestone used in this study is collected from Saraburi province. Approximately 3,000 kg of material is transported to Chulalongkorn University's laboratory in Bangkok. This crushed limestone source is generally used in road construction. This material is selected as a representative of the unbound granular material of Thailand.

The gradation of crushed limestone used in this study is selected by researcher. There are two different gradations. In this study, these gradations will be referred as G1 and G2. The power-0.45 particle size distribution curve of both G1 and G2 are shown in figure 3.1. According to DH-S 202/2531 standard, the G1 and G2 can be classified in class C. Since the specimen size is 100mm dia. by 200mm height, the maximum particle size shall not exceed 25mm.

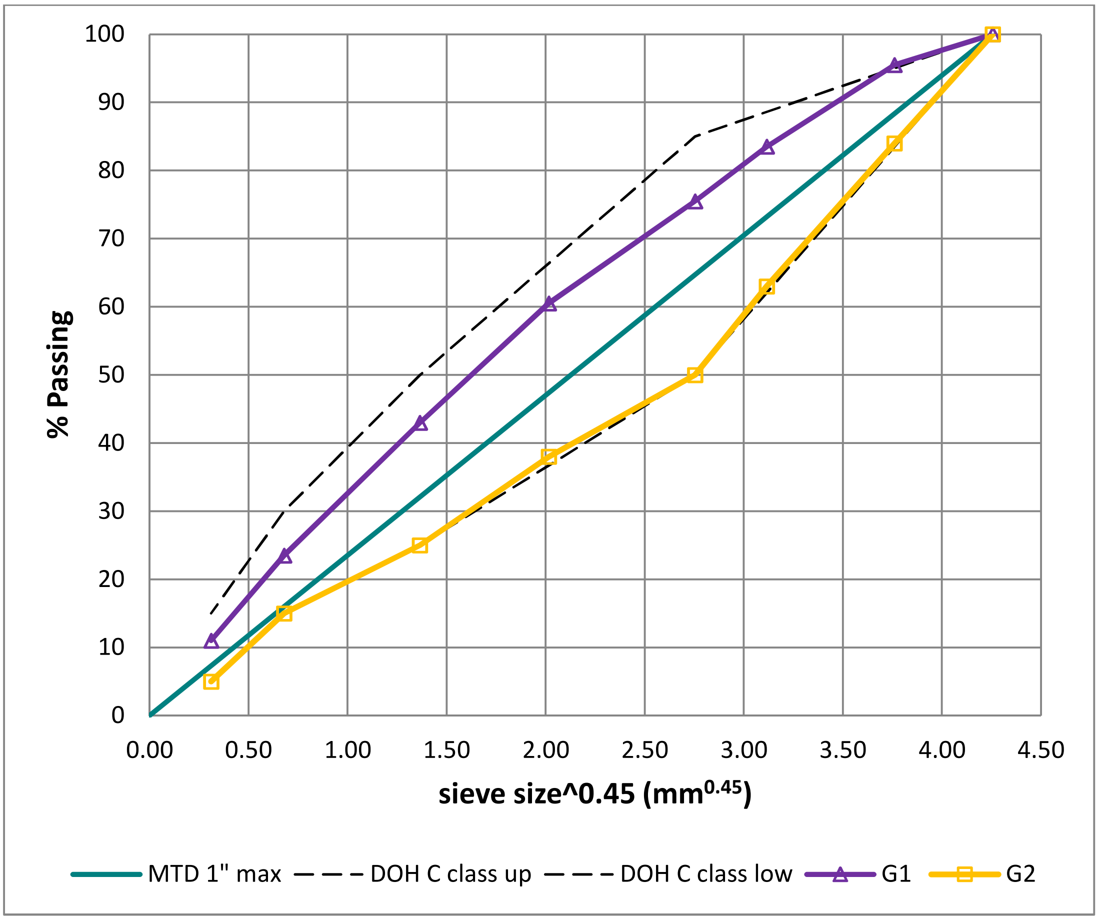


Figure 3.1 G1 and G2 power-0.45 particle size distribution

3.3 Basic Properties Testing

The basic properties of the crushed limestone are tested as list as follow:

3.3.1 Bulk specific gravity of coarse aggregate

The 12.5mm (1/2") and 9.5mm (3/8") aggregate particle are tested according to ASTM C127 and AASHTO T85 “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate”.

3.3.2 Bulk specific gravity of fine aggregate

The 0.425mm (No.40) aggregate particle is tested according to ASTM C128 and AASHTO T84 “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate”.

From the bulk specific gravity test of both coarse and fine aggregates, the average density, specific gravity and the absorption of the coarse and fine aggregates are determined. These results are used to calculate the zero air void line (ZAV) in the modified compaction test.

3.3.3 Modified Compaction test

The G1 and G2 gradations are tested the modified compaction test according to ASTM D1557 and AASHTO T180 “Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft lbf/ft^3 (2,700 kN m/m^3)). The maximum dry density (MDD) and optimum moisture content (OMC) are determined.

3.3.4 California Bearing Ratio (CBR) test

The CBR values of G1 and G2 are determined according to ASTM D1883 and AASHTO T193 “Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils”. These values are used to evaluate the strength of materials using in pavement structure.

3.4 Experimental Design

Since the main objective is to study influences of the key parameters affected to the resilient modulus of the selected unbound granular materials, the test specimens will be prepared in the cylindrical shape with 100mm. dia. by 200mm. height. The main variable parameters in this study are the water content and compaction level. The aggregate gradation has two types. The first variable parameter, compaction level or %modified compaction, varies at 2 levels. The second variable parameter, water content, varies at 5 levels. However, in some case, due to the difficulty to produce the specimens, the variable level will be missing.

3.5 Details of Testing Program

3.5.1 Sample Preparation Method

In this study, the specimens are produced in the cylindrical shape with 100mm dia. by 200mm height. Each specimen weight is calculated using %modified compaction to meet specified mold volume. Before compact the specimen, the weighted specimen is mixed with desired water content. Then leave it in the closed plastic bag for 24 hours. In this step, the water can be well mixed to all particles. This step will help the specimen to easier compact at low water content.

To compact specimen to the desired density, the KANGO vibrating hammer, model 950KV, is used. The compaction procedure refers to EN 13286-4 “Unbound and hydraulically bound mixtures – Part 4: Test methods for laboratory reference density and water content – Vibrating hammer”. The vibrating hammer is shown in figure 3.2. To eject the sample out of the mold with care, the 3-parts split mold with collar is used.

Figure 3.2 The KANGO 950KV vibrating hammer with split mold

Figure 3.3 Weighting sample for one compact layer (Left), during compaction (Right)

To achieve better uniform density, the sample weight is divided by 4 layers equally and compact each layer to approximately 5cm height. The compacted specimen is weighted and measured diameter and height to check the desired density.

Figure 3.4 Weighting compacted sample (Left), compacted sample size measurement (Right)

The final preparation step is to fit the rubber membrane around specimen. Then assembly the top chamber of triaxial cell and put the cell into testing position.

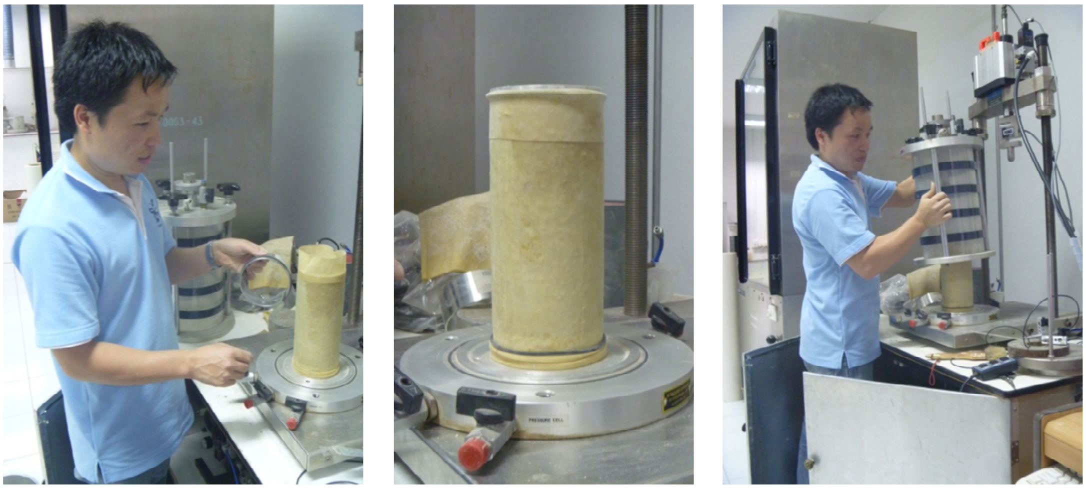


Figure 3.5 Fit the rubber membrane (Left), the sample ready to test (Middle), assembly triaxial cell (Right)

3.5.2 Repeated-Load Triaxial Test System

The repeated-load triaxial test is conducted at the asphalt research laboratory, Bureau of Road Research and Development, Department of Highway, using the IPC Global UTM-14P closed-loop servo-pneumatic universal testing machine. The load frame has 14 kN capacity actuator with 30mm stroke. The maximum load, at 10 Hz, is 12 kN. The RLT system is the computer-controlled with the state-of-the art IMACS controller. The IMACS has two closed-loop feed-back control channels which can control cyclic load and confining pressure simultaneously and independently. Figure 3.6 shows the repeated-load triaxial test system setup with triaxial cell.

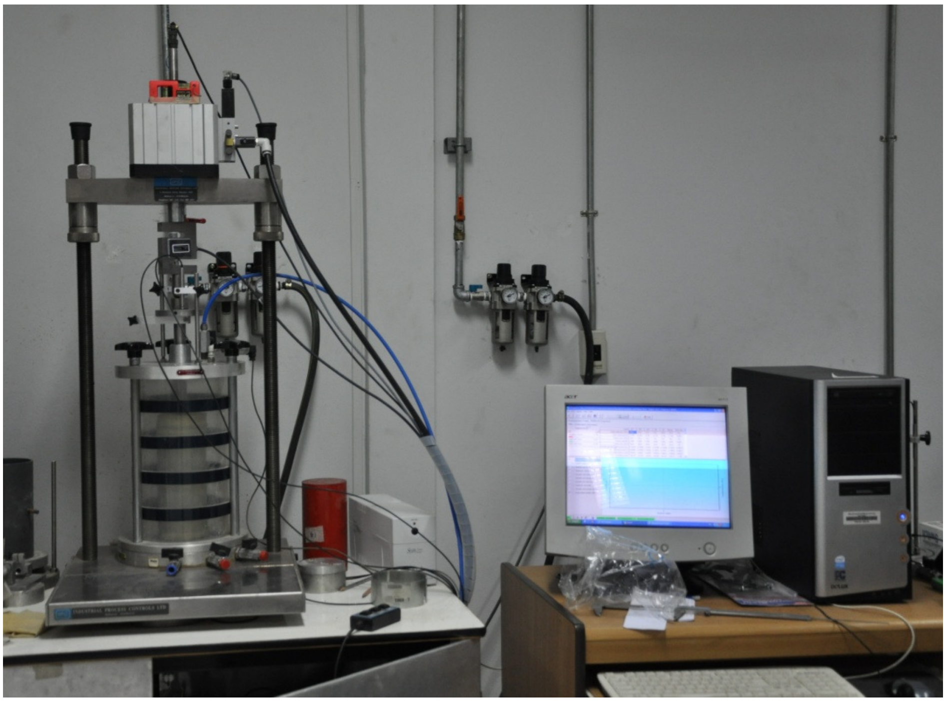


Figure 3.6 Repeated-load triaxial test system setup with triaxial cell

The UTM-14P can be performed the resilient modulus test using the UTS009 software for “Unbound Material Resilient Modulus and Shear Test”. This software refers to AASHTO T307 standard.

3.5.3 Resilient Modulus Test

The resilient modulus is the main testing result of this study. The test procedure refers to AASHTO T307-99 (2007) “Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials”. The selected materials are classified as base/subbase material. The testing sequence for base/subbase material is shown in table 3.1.

Table 3.1 Testing sequences for Base/Subbase materials

Sequence No.	Confining pressure (kPa)	Max Axial Stress (kPa)	Cyclic Stress (kPa)	Contact Stress (kPa)	No. of Load Applications
0	103.4	103.4	93.1	10.3	500-1000
1	20.7	20.7	18.6	2.1	100
2	20.7	41.4	37.3	4.1	100
3	20.7	62.1	55.9	6.2	100
4	34.5	34.5	31.0	3.5	100
5	34.5	68.9	62.0	6.9	100
6	34.5	103.4	93.1	10.3	100
7	68.9	68.9	62.0	6.9	100
8	68.9	137.9	124.1	13.8	100
9	68.9	206.8	186.1	20.7	100
10	103.4	68.9	62.0	6.9	100
11	103.4	103.4	93.1	10.3	100
12	103.4	206.8	186.1	20.7	100
13	137.9	103.4	93.1	10.3	100
14	137.9	137.9	124.1	13.8	100
15	137.9	275.8	248.2	27.6	100

The G1 gradation is tested to determine the resilient modulus using variables as shown in table 3.2

Table 3.2 Resilient modulus test variable parameters of G1 gradation

Variables	Detail of change	Level of change
%Water content	2.0, 3.25, 4.5, 5.5, 6.5	5
%modified compaction	97 , 103	2
Total testing case		10

Since the G2 is selected after the G1 resilient modulus tests are end, the variables of G2 gradation are selected relatively to G1 variables. The variables of G2 gradation to determine the resilient modulus are shown in table 3.3

Table 3.3 Resilient modulus test variable parameters of G2 gradation

Variables	Detail of change	Level of change
%Water content	2.0, 3.25, 4.4	3
%modified compaction	100	1
Total testing case		3

For all resilient modulus test cases, 3-replicates of specimens are tested on each variable case. Every resilient modulus test specimens, at the end of test sequence, the quick shear tests are performed. Because each testing case has 3 samples, the quick shear tests are applied in different stress path.

CHAPTER IV

RESULTS, ANALYSIS AND DISCUSSION

4.1 Basic Properties of Unbound Granular Material

4.1.1 Bulk Specific Gravity

The ASTM C127-12 and ASTM C128 procedure are used to determine the bulk specific gravity (Gsb) of the coarse-sized and fine-sized limestone aggregates in this study. The results of three different sizes of limestone aggregates are presented in Table 4.1.

Table 4.1 Bulk specific gravity of limestone aggregates

Aggregate on sieve size	Bulk Specific Gravity (Gsb)
25mm – 12.5mm	2.705
9.5mm – 2mm	2.695
0.425mm and smaller	2.667

The bulk specific gravity of the two aggregate blends G1 and G2 are determined based on the Gsb in Table 4.1 using the equation 4.1 (Roberts et.al, 1996).

$$G_{avg} = (P_1+P_2+P_3+\ldots)/(P_1/G_1 + P_2/G_2 + P_3/G_3 +\ldots) \qquad (4.1)$$

Where

G_{avg} = average specific gravity of blended aggregates consisting of fraction 1,2,3,…

G1, G2 , G3,…= specific gravity of fraction 1,2,3,…

P1, P2 , P3,… = weight percentages of fraction 1,2,3,… (P1+ P2 + P3+… =100)

The averaged Gsb of G1 is 2.684 and 2.692 for G2.

Table 4.2 Calculation of bulk specific gravity of G1 and G2 aggregate blends

Sieve size (mm)	G1 %Passing	G1 %Retain indiv	Gsb by size	Gsb x %retain	G2 %Passing	G2 %Retain indiv	Gsb by size	Gsb x %retain
50 (2 ")								
25.0 (1 ")	100	0	2.705	0.00	100	0	2.705	0.00
19.0 (3/4 ")	95.5	4.5	2.705	12.17	84	16	2.705	43.28
12.5 (1/2 ")	83.5	12	2.705	32.46	63	21	2.705	56.81
9.5 (3/8 ")	75.5	8	2.695	21.56	50	13	2.695	35.03
4.75 (# 4)	60.5	15	2.695	40.42	38	12	2.695	32.34
2.00 (# 10)	43	17.5	2.695	47.16	25	13	2.695	35.03
0.425 (# 40)	23.5	19.5	2.667	52.00	15	10	2.667	26.67
0.075 (# 200)	11	12.5	2.667	33.33	5	10	2.667	26.67
Pan	0	11	2.667	29.33	0	5	2.667	13.33
		100	Gsb avg.=	2.684		100	Gsb avg.=	2.692

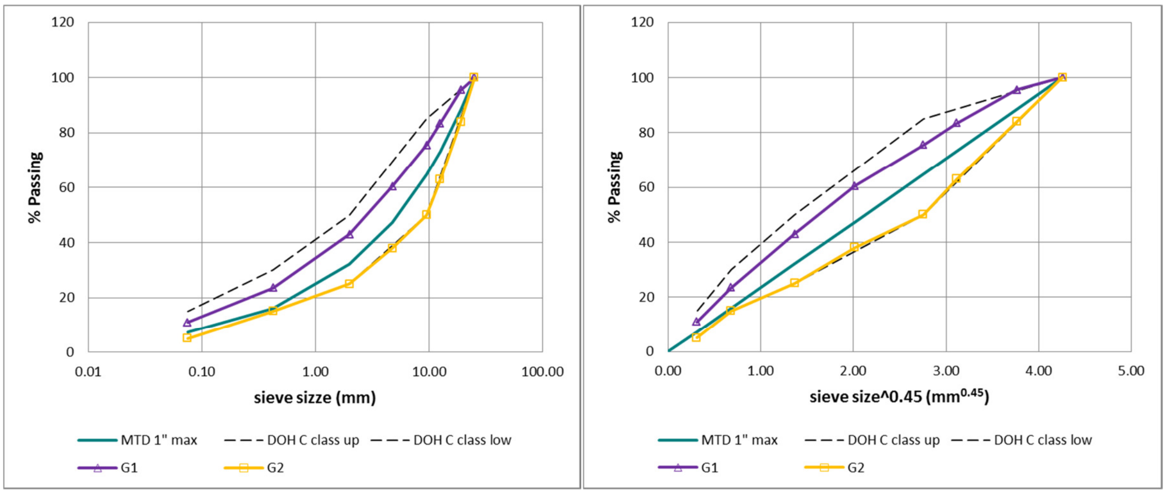


Figure 4.1 Gradation graph of G1 and G2 compared to the DOH specification and Maximum Theoretical Density line.

4.1.2 Modified Compaction Test

The results of modified compaction tests conducted on the G1 and G2 samples are shown in Figure 4.1 and 4.2. Note that the zero air void line (ZAV) represents the boundary line at which a sample cannot have its dry density and water content reach over. The ZAV line is plotted from the relationship between %water content and dry density with 100% saturation as shown in equation 4.2.

$$\gamma_{d\ zav} = \frac{G_{sb}\gamma_w}{1+wG_s} \tag{4.2}$$

Where

γ_{dZAV} = dry density at zero air void state
γ_w = density of water
G_{sb} = bulk specific gravity of material
w = water content of material

While equation 4.2 does not account for some amount of water absorbed into the aggregates' pores, an adjustment is made to deduct a certain percentage of water absorption by the aggregates from the total water content, i.e. w_{adj} = w - %absorption. Based on the bulk specific gravity tests conducted earlier, an average of 1.0% water absorption is introduced to obtain the adjusted ZAV line locating above the original ZAV line in Figure 4.2 and 4.3. The modified compaction graphs show that the fine-graded G1 has a maximum dry density of 2.35 g/cm^3 at 4.8% optimum water content and the coarse-graded G2 has a maximum dry density of 2.42 g/cm^3 at 4.4% optimum water content.

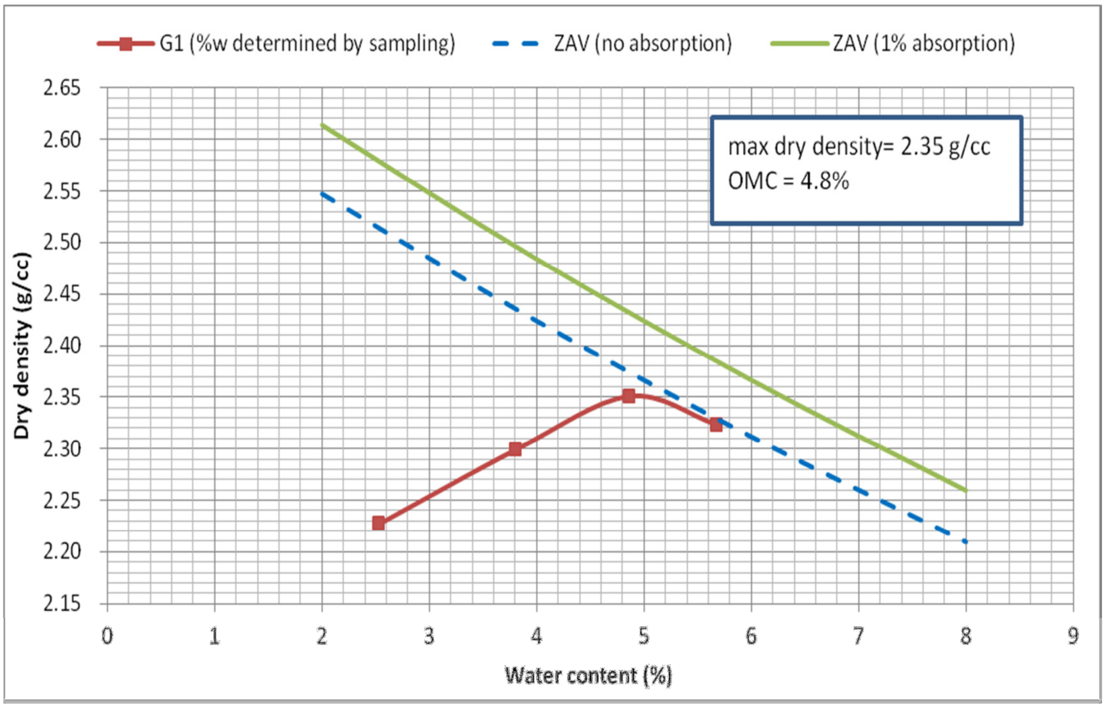


Figure 4.2 Modified compaction graph of crushed limestone gradation G1.

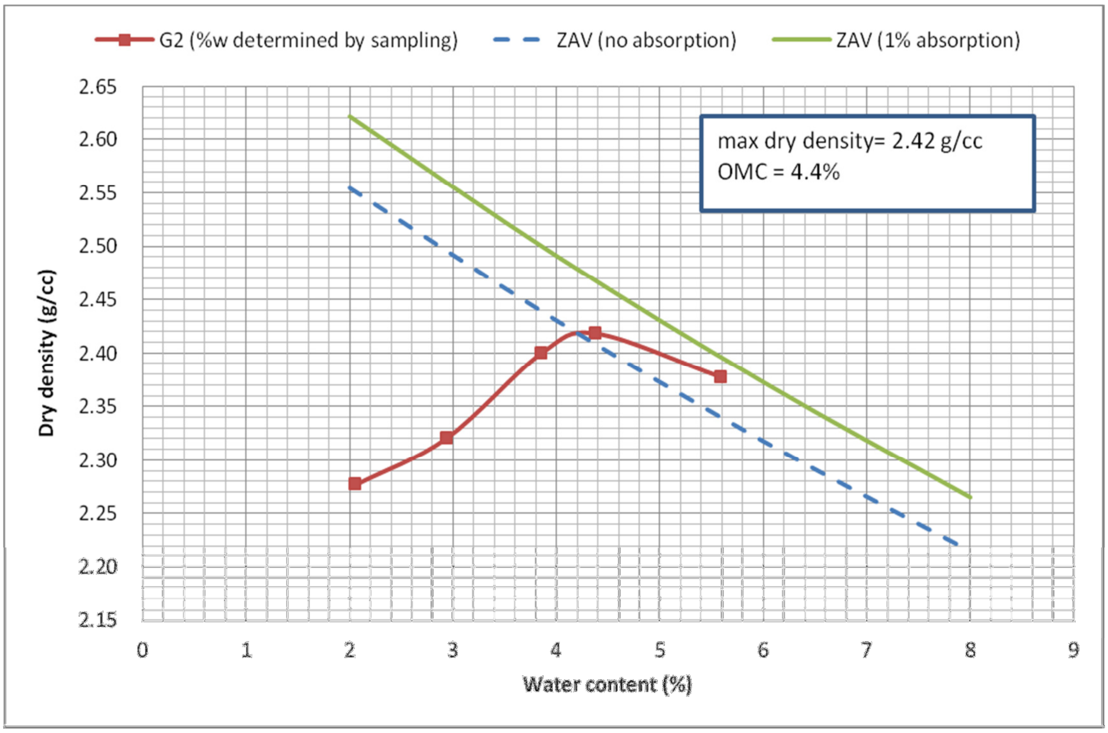


Figure 4.3 Modified compaction graph of crushed limestone gradation G2.

4.1.3 California Bearing Ratio (CBR)

In this study, the AASHTO T193 testing standard is followed to conduct the determination of the CBR of the G1 and G2 materials. Three samples of G1 material all prepared at the optimum moisture content are compacted at three different compaction levels using modified compaction hammer in the 150mm diameter sized molds. The samples dimensions, weights and moisture contents are measured for determining their dry densities. The compacted samples are left in mold and soaked under water for 96 hours (4 days) before conducting the bearing force and penetration measurement. The details of load and penetration for all samples are included in the Appendix. The graphs of %CBR at 0.1 inch and 0.2 inch penetration at three different dry densities are presented in Figure 4.4 and 4.5.

For G1 gradation, a sample prepared at 100% modified compaction i.e. 2.35 g/cm^3 dry density will have 95%CBR @0.1inch penetration and 132%CBR @0.2 inch penetration. For G2 gradation, a sample prepared at 100% modified compaction i.e. 2.42 g/cm^3 dry density will have 129%CBR @0.1inch penetration and 172%CBR @0.2 inch penetration. Therefore at the same compaction energy level, the coarse gradation G2 has a higher %CBR than the fine gradation G1. However, if a G1 sample is prepared at the same dry density 2.42 g/cm^3 as the G2 sample, the G1 sample will have 153%CBR @0.1inch penetration and 212%CBR @0.2 inch penetration higher than the G2 sample.

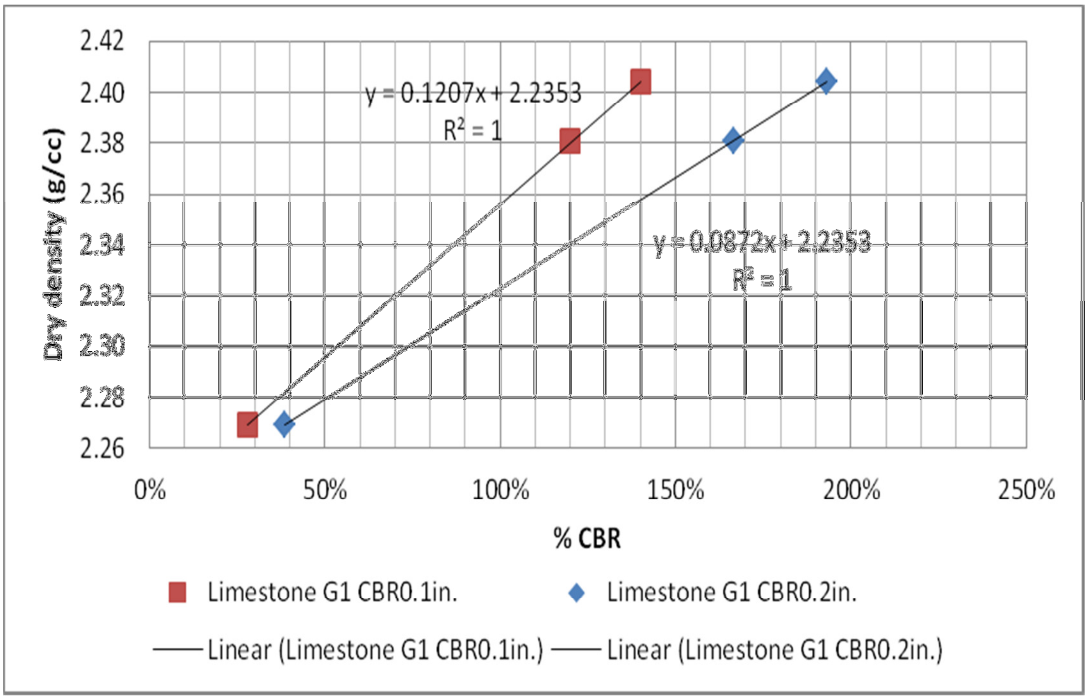


Figure 4.4 %CBR vs. dry density graph of G1 fine-graded crushed limestone.

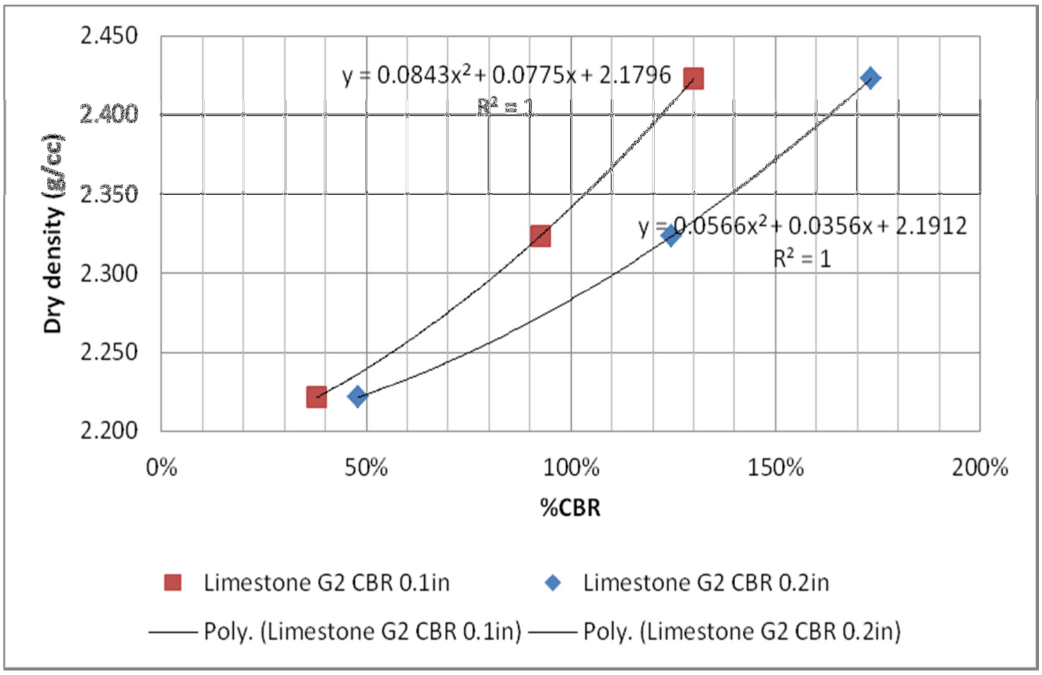


Figure 4.5 %CBR vs. dry density graph of G2 coarse-graded crushed limestone.

4.2 Resilient Modulus Test Results

According to the experimental design in the stage of testing resilient modulus (Mr), a number of 100mmx200mm cylinder-shaped samples are prepared and compacted to meet the target %water content and %modified compaction by using a vibratory compactor. The dimensions and weight of all samples after extrusion from the mold are recorded. And after those samples are done from the resilient testing procedure, they are measured the moisted weight and oven-dried weight for determining the actual water content of the sample after the test. The sample descriptions are summarized in Table 4.3 – 4.5. The tables show that the sample preparation process can produce the samples up to the target level, although there is some variation of %water content and %compaction due to the fact that actual %water content is determined using the sample weight after completion of the test at which an amount of water loss to the rubber membrane is noticed and this results in the calculated values of dry density and %compaction.

Table 4.3 Summary of sample preparation for G1 targeting at 97 % modified compaction

Sample no.	replicate no.	Date of test	%w after test	γdry (g/cm^3)	Void ratio, e	%saturation	Actual %compaction
CR_G1_2.0_97_1MR	1	29/11/12	2.36	2.119	26.65	23.78	90.18
CR_G1_2.0_97_2MR	2	04/12/12	2.23	2.215	21.17	28.12	94.26
CR_G1_2.0_97_3MR	3	04/12/12	1.83	2.204	21.79	22.53	93.78
CR_G1_2.0_97_4MR	4	07/12/12	2.18	2.234	20.16	29.07	95.05
CR_G1_3.25_97_1MR	1	29/11/12	3.19	2.152	24.72	34.60	91.57
CR_G1_3.25_97_2MR	2	29/11/12	2.79	2.248	19.40	38.64	95.66
CR_G1_3.25_97_3MR	3	29/11/12	3.24	2.239	19.89	43.67	95.26
CR_G1_3.25_97_4MR	4	08/02/13	3.58	2.307	16.34	58.79	98.17

Sample no.	replicate no.	Date of test	%w after test	γdry (g/cm^3)	Void ratio, e	%saturation	Actual %compaction
CR_G1_3.25_97_5MR	5	08/02/13	3.55	2.297	16.85	56.54	97.74
CR_G1_4.5_97_2MR	1	30/11/12	4.17	2.295	16.92	66.20	97.68
CR_G1_4.5_97_3MR	2	30/11/12	3.86	2.262	18.67	55.53	96.25
CR_G1_4.5_97_4MR	3	08/02/13	4.51	2.329	15.26	79.24	99.09
CR_G1_5.5_97_1MR	1	30/11/12	5.61	2.247	19.44	77.51	95.63
CR_G1_5.5_97_2MR	2	04/12/12	5.08	2.279	17.78	76.72	96.97

Table 4.4 Summary of sample preparation for G1 targeting at 103% modified compaction

Sample no.	replicate no.	Date of test	%w after test	γdry (g/cm^3)	Void ratio, e	%saturation	Actual %compaction
CR_G1_2.0_103_1MR	1	14/01/13	1.96	2.265	18.51	28.42	96.39
CR_G1_2.0_103_2MR	2	14/01/13	2.20	2.284	17.54	33.69	97.19
CR_G1_3.25_103_2MR	2	14/01/13	3.20	2.396	12.04	71.31	101.96
CR_G1_3.25_103_3MR	3	14/01/13	3.40	2.369	13.32	68.51	100.81
CR_G1_4.5_103_1MR	1	10/01/13	5.01	2.379	12.84	104.64	101.23
CR_G1_4.5_103_2MR	2	10/01/13	6.10	2.382	12.71	128.85	101.35
CR_G1_4.5_103_3MR	3	10/01/13	4.55	2.413	11.23	108.66	102.70
CR_G1_5.5_103_1MR	1	10/01/13	5.27	2.432	10.40	136.05	103.47
CR_G1_5.5_103_2MR	2	10/01/13	4.81	2.434	10.29	125.44	103.57
CR_G1_5.5_103_3MR	3	10/01/13	3.49	2.459	9.19	102.01	104.62

Table 4.5 Summary of sample preparation for G2 targeting 100 % modified compaction

Sample no.	replicate no.	Date of test	%w after test	γdry(g/cm^3)	Void ratio, e	%saturation	Actual %compaction
CR_G2_2.0_100_1MR	1	20/02/13	1.94	2.382	13.05	39.44	98.39
CR_G2_2.0_100_2MR	2	20/02/13	1.97	2.332	15.42	33.82	96.36
CR_G2_2.0_100_3MR	3	20/02/13	1.93	2.370	13.55	37.69	97.95
CR_G2_3.25_100_1MR	1	20/02/13	3.09	2.460	9.67	86.27	101.64
CR_G2_3.25_100_2MR	2	20/02/13	3.14	2.431	10.98	77.08	100.44
CR_G2_3.25_100_3MR	3	20/02/13	3.15	2.438	10.64	79.75	100.75
CR_G2_4.4_100_1MR	1	25/01/13	4.22	2.391	12.58	88.78	98.79
CR_G2_4.4_100_2MR	2	25/01/13	4.31	2.413	11.54	98.62	99.72
CR_G2_4.4_100_3MR	3	25/01/13	4.16	2.413	11.54	95.31	99.72

The void ratio (e) and %saturation in the Tables are calculated using the following definitions and equations.

$$\text{Void ratio, } e = (Gsb*\gamma_w)/(\gamma_d - 1) \tag{4.3}$$

$$\%\text{saturation} = (\%w*Gsb)/e \tag{4.4}$$

Where

γ_w = density of water

γ_d = dry density of materials

G_{sb} = bulk specific gravity of material

w = water content of material

The results of determining the resilient modulus of samples prepared at the designed values of interested parameters are summarized in Table 4.6 – 4.18. And the graphs illustrating the averaged resilient modulus from the replicate samples of the same parameters setting (%modified compaction and %water content) at 15 loading sequences are shown in Figure 4.6, 4.7 and 4.8. There are a few remarks that can be drawn from the graphs:

- Mr values of the crushed limestone UGM regardless of the stress states vary in the range of 100 to 500 MPa.
- All of the Mr graphs indicate the same evidence that %water content has an influence on the Mr value for both G1 and G2. The lower %water content, the higher Mr value.
- At a given %water content, the Mr value increases with the increasing loading sequences. The Mr value is dependent on the applied stress state. As the confining stress and deviatoric stress increase, the Mr increases as well.
- The graphs indicate that Mr values of the samples prepared at 103% modified compaction are in the same level as those of samples prepared at 97% modified compaction. So, the level of compaction effort may not sensitively influence the resilient modulus of the crushed limestone UGM.

Note that there are some Mr values missing from the graph columns in Figure 4.6 - 4.8 because those Mr values have too high standard deviaiton during the Mr measurement and are excluded from the results for further analysis. The high deviation of Mr values happen when the samples experienced either some instability or failure from excessive vertical deformation. As such, on some samples the tests are terminated before reaching the sequence no.15. Those failure cases can happen in the samples with high %water content and subjected to high stress magnitude in higher loading sequences.

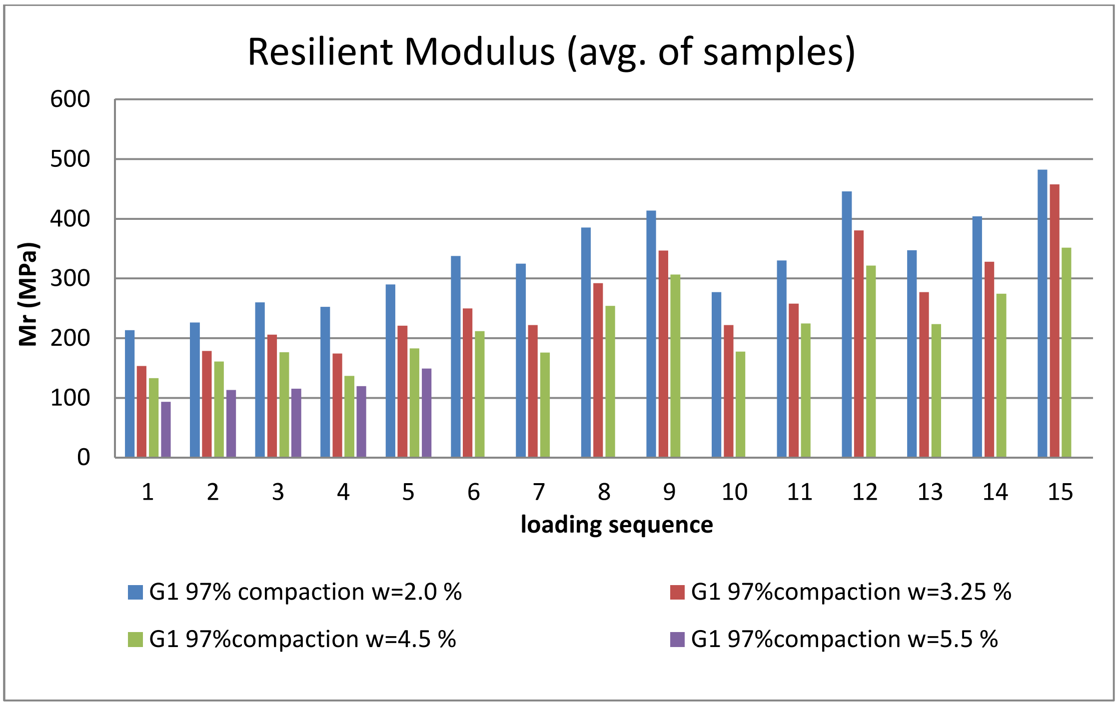


Figure 4.6 Resilient modulus of G1 97% modified compaction

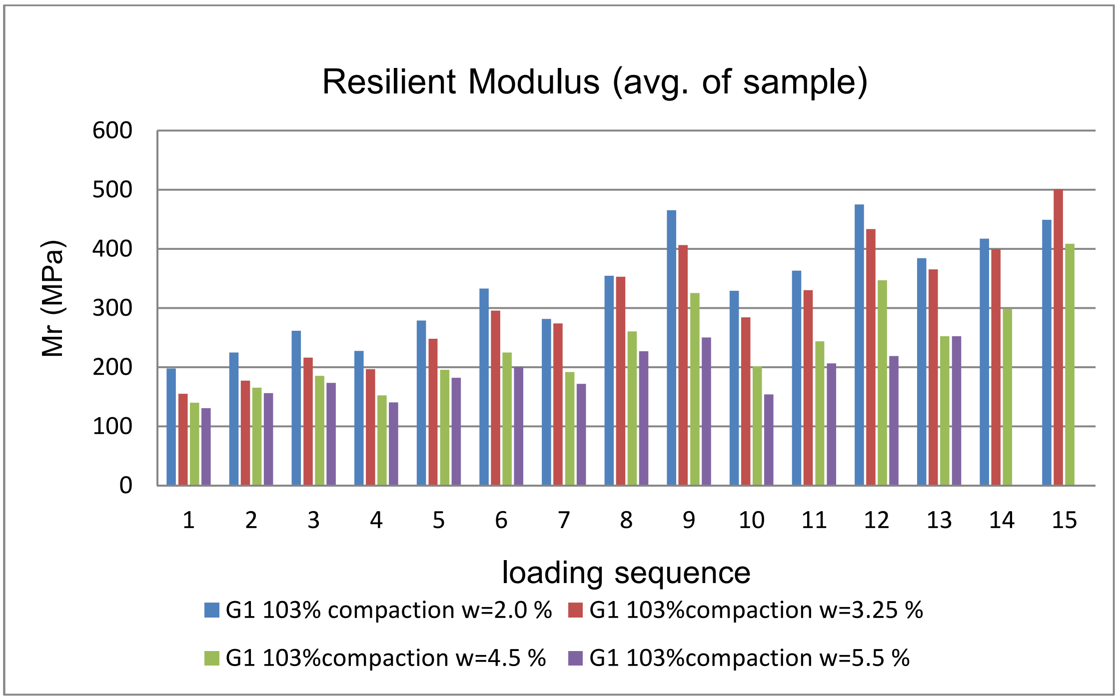


Figure 4.7 Resilient modulus of G1 103% modified compaction

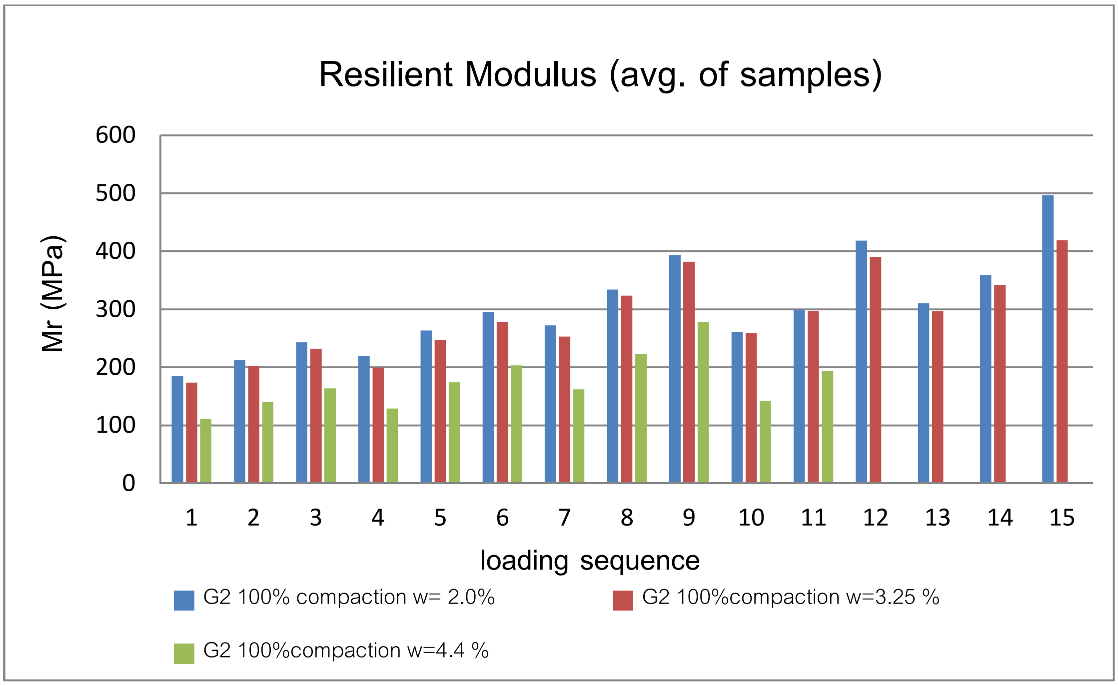


Figure 4.8 Resilient modulus of G2 100% modified compaction

Table 4.6 Results of resilient modulus of G1 97% modified compaction w2.0%

	G1 97% compaction w=2.0 %								Avg.of cured samples
Sample ID	sample 1		sample 2		sample 3		sample 4		
Sequence	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)
1	121	1.7	134	0.4	131	1.0	214	0.7	214
2	139	0.5	142	0.6	143	0.5	226	0.6	226
3	175	0.7	168	0.5	168	0.5	260	1.2	260
4	135	0.4	153	0.9	157	0.4	253	0.7	253
5	186	1.2	187	0.7	185	0.3	290	0.7	290
6	226	1.1	225	0.5	217	0.4	338	0.6	338
7	188	1.7	192	0.4	207	1.0	325	1.2	325
8	267	0.6	366	1.1	218	0.9	385	0.7	385
9	264	3.8	512	6.0	303	1.0	414	0.9	414
10	302	1.2		0.7	198	1.0	277	1.0	277
11	417	0.4		0.8	241	0.4	330	0.7	330
12							446	0.6	446
13							347	0.5	347
14							404	0.8	404
15							482	0.6	482
Curing status	No cured		No cured		No cured		cured		
dry density (g/cc)	2.119		2.215		2.204		2.234		
%mod.Compaction actual	90.18		94.26		93.78		95.05		
%water actual	2.36		2.23		1.83		2.18		
% Saturation	23.78		28.21		22.53		29.07		
% e	26.65		21.17		21.79		20.16		

Table 4.7 Results of resilient modulus of G1 97% modified compaction w 3.25%

	G1 97%compaction w=3.25 %						Repeatition on 08/02/2013				Avg.of cured samples
Sample ID	sample 1		sample 2		sample 3		sample 4		sample 5		
Sequence	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)
1	139	0.3	112	0.3	136	0.9	156	0.2	151	0.6	154
2	148	0.4	130	0.8	151	0.4	186	0.8	172	0.3	179
3	161	0.3	152	0.7	171	0.6	216	0.8	195	0.6	206
4	156	0.2	138	0.6	159	0.3	179	0.2	169	0.5	174
5	173	0.3	172	0.4	188	0.5	232	0.3	210	0.5	221
6	191	0.6	206	0.5	211	0.2	265	0.4	236	0.4	250
7	223	0.4	197	0.5	213	0.7	230	0.7	214	0.4	222
8	247	0.1	260	0.4	257	0.1	310	0.3	274	0.3	292
9	290	0.3	321	0.7	317	1.2	373	0.6	321	0.2	347
10	322	1.3	234	1.0	230	0.8	230	0.7	214	0.4	222
11	290	0.5	239	0.3	244	0.5	266	0.4	250	0.5	258
12	311	0.5	343	0.9	344	0.6	394	0.2	367	0.5	380
13	397	1.2	276	1.6	273	0.8	278	0.3	276	0.4	277
14		0.4	294	0.7	299	0.4	325	0.4	331	0.6	328
15		0.5	419	1.9	421	0.6	460	0.4	456	0.7	458
Curing status	No cured		No cured		No cured		cured		cured		
dry density (g/cc)	2.152		2.248		2.239		2.307		2.297		
% mod. Compaction actual	91.57		95.66		95.26		98.17		97.74		
%water actual	3.19		2.79		3.24		3.58		3.55		
% Saturation	34.60		38.64		43.67		58.79		56.54		
%e	24.72		19.40		19.89		16.34		16.85		

Table 4.8 Results of resilient modulus of G1 97% modified compaction w 4.5%

	G1 97%compaction w=4.5 %						Avg.of cured samples
Sample ID	sample 2		sample 3		sample 4		
Sequence	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)
1	95	0.2	124	0.5	133	0.3	133
2	114	0.3	144	0.2	161	0.5	161
3	132	0.4	165	0.3	177	0.6	177
4	110	0.6	139	0.6	137	0.7	137
5	142	0.5	180	0.4	183	0.1	183
6	159	0.2	208	0.5	212	0.2	212
7					176	0.4	176
8					254	0.4	254
9					307	0.4	307
10					177	0.6	177
11					225	0.4	225
12					322	0.3	322
13					224	0.3	224
14					275	0.4	275
15					352	0.4	352
Curing status	No cured		No cured		cured		
dry density (g/cc)	2.30		2.26		2.33		
% mod. Compaction actual	97.68		96.25		99.09		
%water actual	4.17		3.86		4.51		
% Saturation	66.20		55.53		79.24		
%e	16.92		18.67		15.26		

Table 4.9 Results of resilient modulus of G1 97% modified compaction w 5.5%

	G1 97%compaction w=5.5 %						Avg.of cured samples
Sample ID	sample 1		sample 2		sample3		
Sequence	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)
1	93	0.2	94	0.2			93
2	115	0.4	112	0.2			115
3	130	0.2	101	0.2			130
4	110	1.0	130	0.5			110
5	142	0.3	157	0.5			142
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
Curing status	Curred		Curred				
dry density g/cc	2.25		2.28				
% mod. Compaction actual	95.63		96.97				
%water actual	5.61		5.08				
% Saturation	77.51		76.72				
e	19.44		17.78				

Table 4.10 Results of resilient modulus of G1 103% modified compaction w 2.0%

	G1 103% compaction w=2.0 %						Avg.of cured samples
Sample ID	sample 1		sample 2		sample 3		
Sequence	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)
1	203	0.8			193	1.1	198
2	220	0.5			230	0.5	225
3	243	0.6			280	1.1	262
4	227	0.4			228	0.9	228
5	255	0.2			303	0.8	279
6	288	0.8			378	0.7	333
7	260	0.6			303	0.8	282
8	321	0.4			389	0.3	355
9	375	0.4			556	0.6	465
10	316	1.2			342	1.0	329
11	317	0.2			409	0.4	363
12	392	0.3			558	1.0	475
13	346	0.8			424	0.8	385
14	356	0.5			479	0.4	417
15	449	0.4				1.2	449
Curing status	cured				cured		
dry density (g/cc)	2.27				2.28		
% mod. Compaction	96.39				97.19		
%water actual	1.96				2.20		
% Saturation	28.42				33.69		
%e	18.51				17.54		

Table 4.11 Results of resilient modulus of G1 103% modified compaction w 3.25%

	G1 103%compaction w=3.25 %						Avg.of cured samples
Sample ID	sample 1		sample 2		sample 3		
Sequence	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)
1			151	0.5	159	0.7	155
2			175	0.7	179	0.8	177
3			211	0.4	222	0.3	216
4			204	0.4	189	0.4	197
5			247	0.7	249	0.5	248
6			277	0.5	314	0.6	296
7			277	0.2	271	0.5	274
8			344	0.3	361	0.5	353
9			395	0.4	418	0.2	406
10			300	0.7	269	2.0	285
11			334	0.6	326	0.6	330
12			435	0.6	432	0.3	433
13			368	0.3	363	0.7	365
14			408	0.4	390	0.7	399
15			508	0.3	494	0.4	501
Curing status			cured		cured		
dry density g/cc			2.396		2.369		
% mod. Compaction			101.96		100.81		
%water actual			3.20		3.40		
% Saturation			71.31		68.51		
%e			12.04		13.32		

Table 4.12 Results of resilient modulus of G1 103% modified compaction w 4.5%

	G1 103%compaction w=4.5 %						Avg.of cured samples
Sample ID	sample 1		sample 2		sample 3		
Sequence	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)
1	121	0.4	152	0.8	147	0.8	140
2	145	0.5	181	0.5	170	0.6	165
3	161	0.3	203	0.3	192	0.6	185
4	130	0.4	167	0.5	160	0.3	152
5	170	0.2	212	0.3	205	0.5	196
6	202	0.3	238	0.5	234	0.3	225
7	168	0.3	203	0.4	204	0.4	192
8	233	0.2	270	0.3	279	0.3	260
9	243	0.4	321	0.1	330	0.4	298
10	340	0.2	204	0.3	207	0.3	251
11	240	0.2	237	0.3	251	0.5	243
12	292	0.3	343	0.4	357	0.3	331
13	193	0.1	255	0.2	262	0.2	237
14			292	0.3	312	0.4	302
15			409	0.3	408	0.6	409
Curing status	cured		cured		cured		
dry density g/cc	2.38		2.38		2.41		
% mod. Compaction	101.23		101.35		102.70		
%water actual	5.01		6.10		4.55		
% Saturation	104.64		128.85		108.66		
%e	12.84		12.71		11.23		

Table 4.13 Results of resilient modulus of G1 103% modified compaction w 5.5%

	G1 103%compaction w=5.5 %						Avg.of cured samples
Sample ID	sample 1		sample 2		sample 3		
Sequence	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)
1	131	0.3	146.8	1.1	114.3	0.6	131
2	156	0.4	171.5	0.3	141.5	0.6	156
3	174	0.3	188.9	0.3	158.5	0.5	174
4	134	0.3	157.4	0.5	131.1	0.1	141
5	181	0.4	198.9	0.4	166.6	0.7	182
6	206	0.4	217.9	0.5	177.3	0.3	201
7	165	0.2	197.2	0.5	154.5	0.4	172
8	233	0.2	252.2	0.3	195.5	0.2	227
9	279	0.1			220.7	0.3	250
10	168	0.4			140.1	0.2	154
11	219	0.5			193.7	0.3	206
12	219	0.7					219
13	252	0.8					252
14							
15							
Curing status	cured		cured		cured		
dry density g/cc	2.432		2.434		2.459		
% mod. Compaction	103.47		103.57		104.62		
%water actual	5.27		4.81		3.49		
% Saturation	136.05		125.44		102.01		
%e	10.40		10.29		9.19		

Table 4.14 Results of resilient modulus of G2 100% modified compaction w 2.0%

	G2 100% compaction w= 2.0%						Avg.of cured samples
Sample ID	sample 1		sample 2		sample 3		
Sequence	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)
1	195	0.8	178	0.7	181	0.5	185
2	229	0.5	204	0.6	206	1.1	213
3	266	0.6	230	0.6	234	0.5	243
4	236	0.5	206	0.5	216	1.0	219
5	287	0.4	250	0.6	253	0.5	263
6	318	0.4	287	0.8	282	0.6	296
7	305	0.5	255	1.0	257	0.9	272
8	364	0.2	326	0.5	312	0.2	334
9	424	0.7	398	0.9	359	1.0	394
10	295	0.5	258	0.2	231	0.3	261
11	335	0.4	292	0.4	270	0.6	299
12	450	0.3	420	0.9	386	0.2	419
13	347	0.3	306	1.2	278	0.4	310
14	397	0.6	350	0.3	329	0.6	359
15	516	0.6	488	0.7	486	0.6	497
Curing status	cured		cured		cured		
dry density g/cc	2.381		2.332		2.370		
% mod. Compaction actual	98.39		96.36		97.95		
%water actual	1.94		1.97		1.93		
% Saturation	39.44		33.82		37.69		
%e	13.05		15.42		13.55		

Table 4.15 Results of resilient modulus of G2 100% modified compaction w 3.25%

	G2 100%compaction w=3.25 %						Avg.of cured samples
Sample ID	sample 1		sample 2		sample 3		
Sequence	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)
1	163	0.4	141	0.4	217	1.0	174
2	199	0.7	178	0.8	231	0.3	202
3	233	0.2	209	0.6	255	0.8	232
4	194	0.6	162	0.4	243	0.7	200
5	249	0.8	218	0.5	276	0.5	247
6	275	0.6	254	0.3	306	0.7	279
7	254	0.3	209	0.5	296	0.5	253
8	312	0.1	295	0.3	363	0.3	324
9	356	0.3	346	0.6	444	0.6	382
10	243	0.4	200	0.4	335	0.5	259
11	279	0.7	243	0.2	368	0.6	297
12	361	0.8	342	0.2	469	0.7	390
13	272	0.2	237	0.4	381	0.6	297
14	317	0.6	285	0.3	423	0.5	342
15	414	0.7	334	1.0	508	0.8	419
Curing status	cured		cured		cured		
dry density g/cc	2.460		2.431		2.438		
% mod. Compaction actual	101.64		100.44		100.75		
%water actual	3.09		3.14		3.15		
% Saturation	86.27		77.08		79.75		
%e	9.67		10.98		10.64		

Table 4.16 Results of resilient modulus of G2 100% modified compaction w 4.4%

	G2 100%compaction w=4.4 %						Avg.of cured samples
Sample ID	sample 1		sample 2		sample 3		
Sequence	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)	S.D.	Mr (MPa)
1	108	0.8	112	0.6	113	0.2	111
2	134	0.3	144	0.6	145	0.3	140
3	155	0.3	170	0.4	173	0.2	164
4	122	0.6	138	1.1	136	0.6	129
5	163	0.2	180	0.6	186	0.3	174
6	200	0.2	200	0.4	207	0.4	204
7	153	0.3			171	0.5	162
8	234	0.4		0.4	211	0.2	223
9	289	0.8			267	0.3	278
10	139	0.5			144	0.4	141
11	207	0.5			180	0.4	194
12	289	0.4					
13	199	0.4					
14	254	0.4					
15							
Curing status	cured		cured		cured		
dry density g/cc	2.391		2.413		2.413		
% mod. Compaction actual	98.79		99.72		99.72		
%water actual	4.22		4.31		4.16		
% Saturation	88.78		98.62		95.31		
%e	12.58		11.54		11.54		

4.3 Correlation between Resilient Modulus and Related Variables

Resilient Modulus results from laboratory testing vary by the testing conditions and properties of specimen preparing condition. A correlation analysis is a reliable tool to find which variables that correlate with the resilient modulus value. The data from Table 4.6 – 4.13 containing the resilient modulus, stresses in the testing conditions and specimen properties such as water content, %saturation, and void ratio, is input into the statistical analysis software to conduct the Pearson correlation.

The results from correlation analysis are shown in table 4.17 for G1-gradation UGM and table 4.18 for G2-gradation UGM.

Table 4.17 Pearson correlation of Mr and related variables for G1 gradation UGM

		MR	σ3	σ1	σd	γd	comp	w	sat	e
MR	Pearson Correlation	1	.658**	.837**	.804**	-.014	-.014	-.361**	-.243**	-.002
	Sig. (2-tailed)		.000	.000	.000	.825	.825	.000	.000	.971
	N	259	259	259	259	259	259	259	259	259
σ3	Pearson Correlation	.658**	1	.860**	.640**	.005	.005	-.072	-.047	-.004
	Sig. (2-tailed)	.000		.000	.000	.935	.935	.249	.447	.948
	N	259	259	259	259	259	259	259	259	259
σ1	Pearson Correlation	.837**	.860**	1	.931**	-.006	-.006	-.089	-.061	.007
	Sig. (2-tailed)	.000	.000		.000	.927	.927	.154	.326	.910
	N	259	259	259	259	259	259	259	259	259
σd	Pearson Correlation	.804**	.640**	.931**	1	-.019	-.019	-.068	-.057	.020
	Sig. (2-tailed)	.000	.000	.000		.765	.765	.279	.363	.750
	N	259	259	259	259	259	259	259	259	259
γd	Pearson Correlation	-.014	.005	-.006	-.019	1	1.000**	.625**	.852**	-.997**
	Sig. (2-tailed)	.825	.935	.927	.765		.000	.000	.000	.000
	N	259	259	259	259	259	259	259	259	259
comp	Pearson Correlation	-.014	.005	-.006	-.019	1.000**	1	.625**	.852**	-.997**
	Sig. (2-tailed)	.825	.935	.927	.765	.000		.000	.000	.000
	N	259	259	259	259	259	259	259	259	259
w	Pearson Correlation	-.361**	-.072	-.089	-.068	.625**	.625**	1	.912**	-.605**
	Sig. (2-tailed)	.000	.249	.154	.279	.000	.000		.000	.000
	N	259	259	259	259	259	259	259	259	259

		MR	$\sigma 3$	$\sigma 1$	σd	γd	comp	w	sat	e
sat	Pearson Correlation	-.243**	-.047	-.061	-.057	.852**	.852**	.912**	1	-.834**
	Sig. (2-tailed)	.000	.447	.326	.363	.000	.000	.000		.000
	N	259	259	259	259	259	259	259	259	259
e	Pearson Correlation	-.002	-.004	.007	.020	-.997**	-.997**	-.605**	-.834**	1
	Sig. (2-tailed)	.971	.948	.910	.750	.000	.000	.000	.000	
	N	259	259	259	259	259	259	259	259	259

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4.18 Pearson correlation of Mr and related variables for G2 gradation UGM

		MR	$\sigma 3$	$\sigma 1$	σd	γd	comp	w	sat	e
MR	Pearson Correlation	1	.621**	.832**	.842**	-.043	-.043	-.435**	-.331**	.056
	Sig. (2-tailed)		.000	.000	.000	.656	.656	.000	.000	.564
	N	110	110	110	110	110	110	110	110	110
$\sigma 3$	Pearson Correlation	.621**	1	.854**	.636**	-.014	-.014	-.121	-.095	.019
	Sig. (2-tailed)	.000		.000	.000	.887	.887	.207	.324	.840
	N	110	110	110	110	110	110	110	110	110
$\sigma 1$	Pearson Correlation	.832**	.854**	1	.944**	-.011	-.011	-.126	-.097	.017
	Sig. (2-tailed)	.000	.000		.000	.912	.912	.188	.314	.863
	N	110	110	110	110	110	110	110	110	110
σd	Pearson Correlation	.842**	.636**	.944**	1	-.007	-.007	-.111	-.084	.012
	Sig. (2-tailed)	.000	.000	.000		.940	.940	.249	.384	.898
	N	110	110	110	110	110	110	110	110	110
γd	Pearson Correlation	-.043	-.014	-.011	-.007	1	1.000**	.537**	.792**	-.999**
	Sig. (2-tailed)	.656	.887	.912	.940		.000	.000	.000	.000
	N	110	110	110	110	110	110	110	110	110
comp	Pearson Correlation	-.043	-.014	-.011	-.007	1.000**	1	.537**	.792**	-.999**
	Sig. (2-tailed)	.656	.887	.912	.940	.000		.000	.000	.000
	N	110	110	110	110	110	110	110	110	110
w	Pearson Correlation	-.435**	-.121	-.126	-.111	.537**	.537**	1	.936**	-.554**
	Sig. (2-tailed)	.000	.207	.188	.249	.000	.000		.000	.000
	N	110	110	110	110	110	110	110	110	110
sat	Pearson Correlation	-.331**	-.095	-.097	-.084	.792**	.792**	.936**	1	-.801**
	Sig. (2-tailed)	.000	.324	.314	.384	.000	.000	.000		.000
	N	110	110	110	110	110	110	110	110	110
e	Pearson Correlation	.056	.019	.017	.012	-.999**	-.999**	-.554**	-.801**	1
	Sig. (2-tailed)	.564	.840	.863	.898	.000	.000	.000	.000	
	N	110	110	110	110	110	110	110	110	110

**. Correlation is significant at the 0.01 level (2-tailed).

Considering Table 4.17 and 4.18, it shows that the G1 and G2 gradation UGMs get the same results that the resilient modulus is highly related to these variables (at 99% confidential level):

- Vertical stress ($\sigma1$)
- Confining stress ($\sigma3$)
- Deviator stress (σd)
- % moisture content (w)
- Degree of saturation (sat)

But the vertical stress and deviator stress are mutually related because $\sigma1 = \sigma d + \sigma3$ while %moisture content has a straight relation with degree of saturation. So, only one variable from many variables that represent the same thing must be chosen to prohibit the mutually exclusive event in regression analysis in the next section. The testing conditions and properties of specimen preparing condition that are chosen to be the variables for regression analysis are vertical stress ($\sigma1$), confining stress ($\sigma3$) and %moisture content (w).

4.4 Regression Analysis of Resilient Modulus Model

In the previous section, the results of the Pearson's correlation of G1 in Table 4.17 and of G2 in Table 4.18 reveal that the resilient modulus (Mr) correlates with the vertical stress ($\sigma1$), confining stress ($\sigma3$) and the %moisture content (w) under the significance level of 0.01. This strong correlation suggests that the relationship between the resilient modulus and the three variables might fit the Equation 2.2 (NCHRP, 2004).

In the Equation 2.2, the bulk stress (θ), the octahedral stress (τ_{oct}) are actually the products of the vertical stress ($\sigma1$), confining stress ($\sigma3$) as presented in the Chapter 2. As such, a linear regression analysis is conducted using the Mr data of the G1 samples with 97% and 103% combined. Since the water content variable is added to the original Equation 2.2, the revised form of equation is proposed in Equation 4.5. Equation 4.6 is the ready form for regression analysis by taking the natural logarithm of Equation 4.5.

$$M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{\text{oct}}}{P_a} + 1\right)^{k_3} (w)^{k_4} \tag{4.5}$$

$$lnM_r = \ln[k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{\text{OCT}}}{P_a} + 1\right)^{k_3} (w)^{k_4}]$$

$$\ln\left(\frac{Mr}{pa}\right) = \ln k_1 + k_2 \ln\left(\frac{\theta}{P_a}\right) + k_3 \ln\left(\frac{\tau_{\text{OCT}}}{P_a} + 1\right) + k_4 \ln(w)$$

Where:

k_1, k_2, k_3, k_4 are constants

Pa = atmospheric pressure = 101.3 kPa

θ = bulk stress $= \sigma_1 + \sigma_2 + \sigma_3$

τ_{oct} = octahedral stress = $\frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}$

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \tag{4.6}$$

Where:

y = $ln\left(\frac{Mr}{P_a}\right)$

x_1 = $ln\left(\frac{\theta}{P_a}\right)$

x_2 = $ln\left(\frac{\tau_{oct}}{P_a} + 1\right)$

β_0 = ln (k_1) $\beta_1 = k_2$ $\beta_2 = k_3$ $\beta_3 = k_4$

The results of linear regression in Table 4.19 reveal that the proposed relationship Equation 4.6 is successfully valid by considering the significance output of the 4 variables in the equation. All 4 variables have earned the significance level of lower than 0.01. The analysis gains the adjusted R^2 of 0.793 with 259 numbers of data points. The constants k_1 to k_4 are presented as follows.

For G1 gradation,

$k_1 = \exp(-0.830) = 0.436$

$k_2 = 0.173$

$k_3 = 1.079$

$k_4 = -0.331$

adjusted R^2=0.793, N= 259

Table 4.19 Result regression of model summary for G1 gradation

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.892[a]	.795	.793	.17362	.795	329.925	3	255	.000

a. Predictors: (Constant), lnw, lnsbulk, lnsoctpa1

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	29.834	3	9.945	329.925	.000[a]
	Residual	7.686	255	.030		
	Total	37.520	258			

a. Predictors: (Constant), lnw, lnsbulk, lnsoctpa1

b. Dependent Variable: lnMpa

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	-.830	.108		-7.717	.000	-1.041	-.618
	lnsbulk	.173	.030	.298	5.819	.000	.114	.231
	lnsoctpa1	1.079	.100	.552	10.789	.000	.882	1.276
	lnw	-.331	.032	-.297	-10.434	.000	-.394	-.269

a. Dependent Variable: lnMpa

For G2 gradation, the process of regression analysis is repeated using the data from G2 samples only. The regression results in Table 4.20 show that all 4 variables have significance level of lower than 0.05 and the adjusted R^2 is 0.810 with 110 number of data points. The constants k_1 to k_4 are presented below.

k_1 = exp(-1.086) = 0.338

k_2 = 0.103

k_3 = 1.053

k_4 = -0.425

adjusted R^2=0.810, N= 110

Table 4.20 Result regression of model summary for G2 gradation

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.903[a]	.815	.810	.14988273255	.815	155.962	3	106	.000

a. Predictors: (Constant), lnwater, ln(soct/pa +1), ln(sbulk/pa)

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	10.511	3	3.504	155.962	.000[a]
	Residual	2.381	106	.022		
	Total	12.892	109			

a. Predictors: (Constant), lnwater, ln(soct/pa +1), ln(sbulk/pa)

b. Dependent Variable: ln(Mr/Pa)

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients			95.0% Confidence Interval for B	
		B	Std. Error	Beta	t	Sig.	Lower Bound	Upper Bound
1	(Constant)	-1.086	.173		-6.279	.000	-1.429	-.743
	ln(sbulk/pa)	.103	.039	.197	2.618	.010	.025	.180
	ln(soct/pa +1)	1.053	.129	.613	8.166	.000	.797	1.308
	lnwater	-.425	.048	-.373	-8.871	.000	-.520	-.330

a. Dependent Variable: ln(Mr/Pa)

Table 4.21 Summary of k constants of resilient modulus relationship model for G1&G2

Gradation	k1	k2	k3	k4	R^2	N
G1	0.436	0.173	1.079	-0.331	0.793	259
G2	0.338	0.103	1.053	-0.425	0.810	110

Thus the resilient modulus model developed from linear regression of the laboratory test data is presented as:

For unbound crushed limestone with G1 gradation,

$$\frac{M_r}{P_a} = 0.436\left(\frac{\theta}{P_a}\right)^{0.173}\left(\frac{\tau_{\mathrm{OCT}}}{P_a}+1\right)^{1.079}(w)^{-0.331} \qquad (4.7)$$

adjusted R^2=0.793, number of data = 259

For unbound crushed limestone with G2 gradation,

$$\frac{M_r}{P_a} = 0.338\left(\frac{\theta}{P_a}\right)^{0.103}\left(\frac{\tau_{\mathrm{OCT}}}{P_a}+1\right)^{1.053}(w)^{-0.425} \quad (4.8)$$

adjusted R^2=0.810, Number of data = 110

Plotting scatter graphs between the actual Mr values from laboratory tests and the calculated Mr using Equation 4.7 and 4.8 are produced for comparing the distribution of data from calculation and lab tests. The plots are illustrated in Fig 4.9 and 4.10 respectively.

Figure. 4.9 shows the Mr values of G1 gradation. The regression model in Equation 4.7 give the calculated Mr values within +/-10% scattering in the below 200 MPa range. After this point, the calculated values are more scatter on both side.

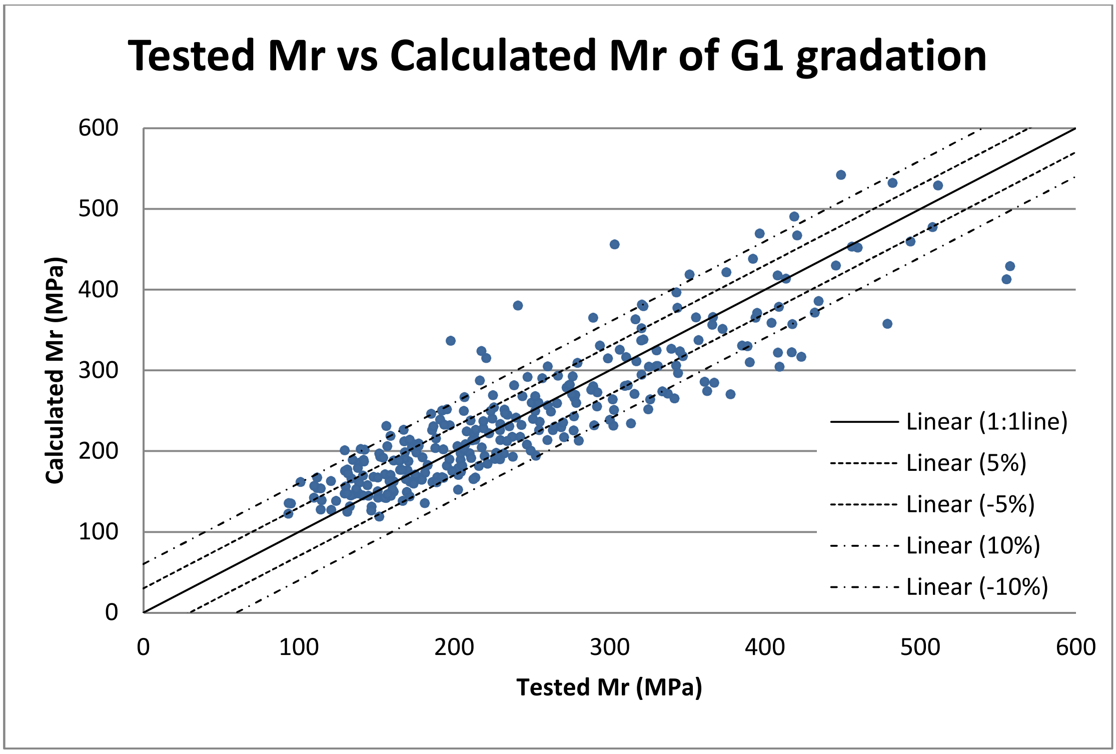


Figure 4.9 relationship between tested Mr and calculated Mr of G1

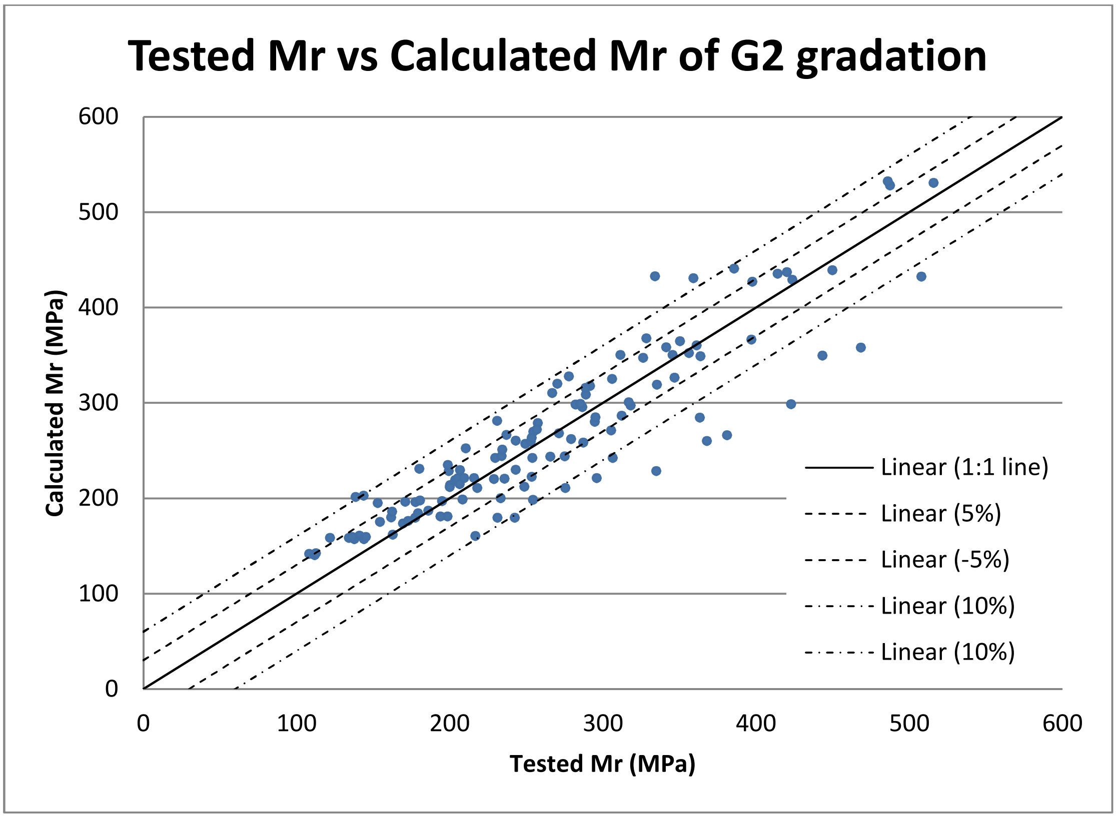


Figure 4.10 relationship between tested Mr and calculated Mr of G2

Figure. 4.10 shows the Mr values of G2 gradation. The regression model in Equation 4.8 give the calculated Mr values within +/-10% scattering in the below 300 MPa range. Since the number of samples in G2 gradation is less than G1 gradation, after 300 MPa, the calculated values are more scatter but in lower value side.

4.5 Influences of Related Variables

From previous part show that many variables related with Resilient Modulus and some are not but important in construction quality. So discussion about related variables with Resilient is below.

4.5.1 Influence of water content

From the regression models of Equation 4.6 and 4.7, the term containing moisture content variable is $(w)^{k4}$ in which the constant k_4 is negative value for both G1 and G2 materials. This fact confirms that as %moisture content increases, the resilient modulus decreases. The graphs in Figure 4.6, 4.8, 4.10 illustrate this evidence.

Also from the Pearson Correlation in Table 4.17 and 4.18, the resilient modulus is highly related to the moisture content in 99% confidential level. And the sign convention of correlation value is minus for both G1 and G2. It means when moisture content increases, resilient modulus of UGM must decrease.

Correlation of Mr and moisture content for G1

		MR	w
MR	Pearson Correlation	1	-.361**
	Sig. (2-tailed)		.000
	N	259	259
w	Pearson Correlation	-.361**	1
	Sig. (2-tailed)	.000	
	N	259	259

Correlation of Mr and moisture content for G2

		Mr	w
Mr	Pearson Correlation	1	-.435**
	Sig. (2-tailed)		.000
	N	110	110
%w	Pearson Correlation	-.435**	1
	Sig. (2-tailed)	.000	
	N	110	110

4.5.2 Influence of compaction Level

From the Pearson Correlation of G1 gradation in Table 4.17, the compaction level is not related to the resilient modulus since the statistic result shows insignificance for both G1 and G2. However, it is not strongly supported to state that the compaction level or the dry density of the specimen does not have any influence on the resilient modulus. This is because in the experimental design, the variation of the compaction level is between ±3% (between 97% and 103%) which may be considered too narrow to let the compaction variable shows its effect on the resilient modulus.

Correlation of Mr and moisture content for G1

		MR	comp
MR	Pearson Correlation	1	-.014
	Sig. (2-tailed)		.825
	N	259	259
comp	Pearson Correlation	-.014	1
	Sig. (2-tailed)	.825	
	N	259	259

Correlation of Mr and moisture content for G2

		MR	comp
MR	Pearson Correlation	1	-.043
	Sig. (2-tailed)		.656
	N	110	110
comp	Pearson Correlation	-.043	1
	Sig. (2-tailed)	.656	
	N	110	110

4.5.3 Influence of stress condition

Determination of the resilient modulus value is dependent of the stress state. The resilient modulus increases with the applied confining and deviatoric stresses level. Thus, defining the resilient modulus of a base material must be accompanied with the referred stress state.

These graphs below show the relationship between resilient modulus, σ_1 and σ_3 that separate by gradation and level of compaction.

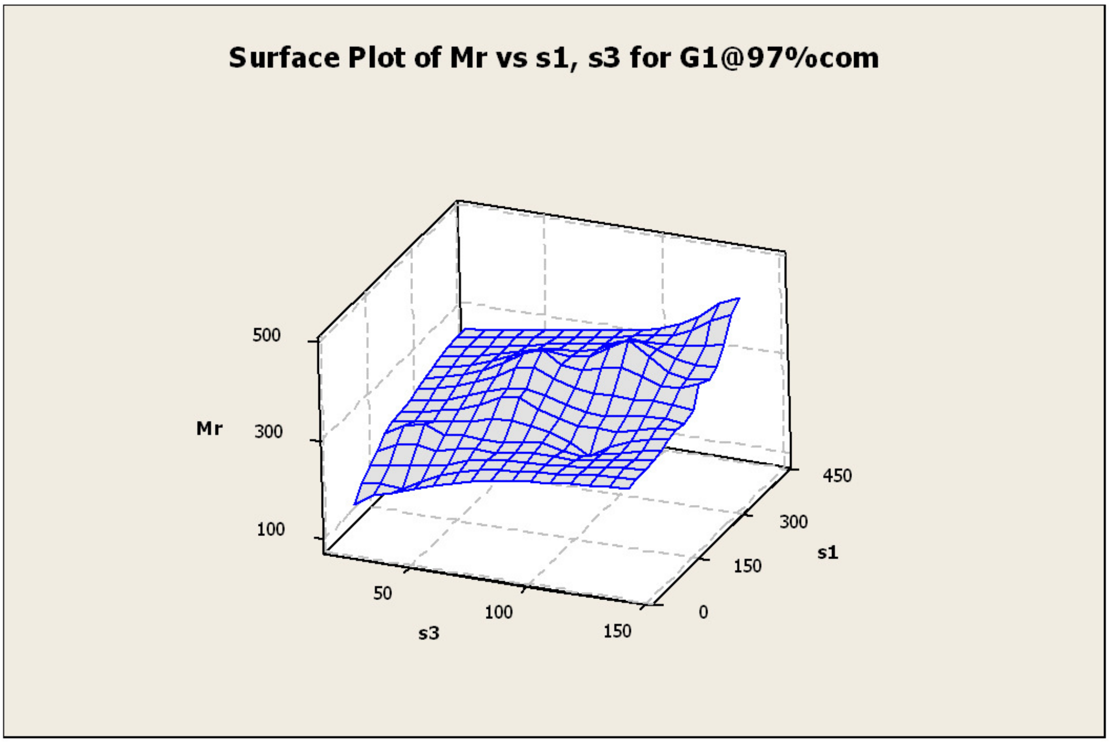


Figure 4.11 Resilient modulus vs stress state plot of G1 97% modified compaction

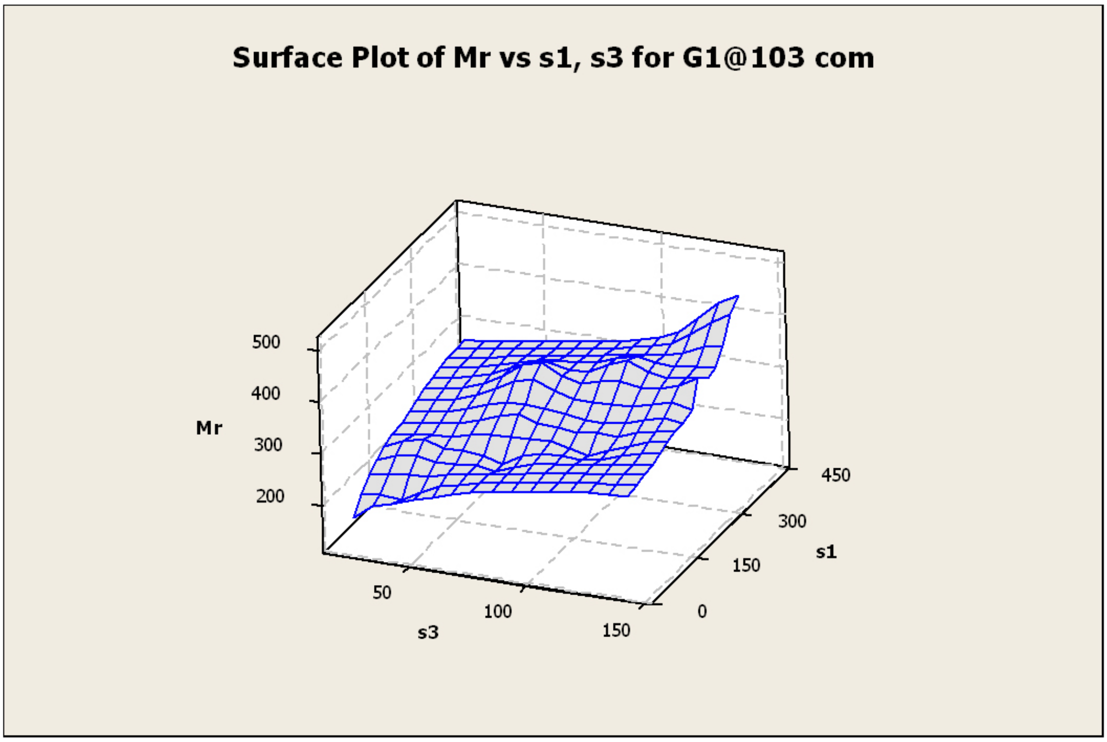


Figure 4.12 Resilient modulus vs stress state plot of G1 103% modified compaction

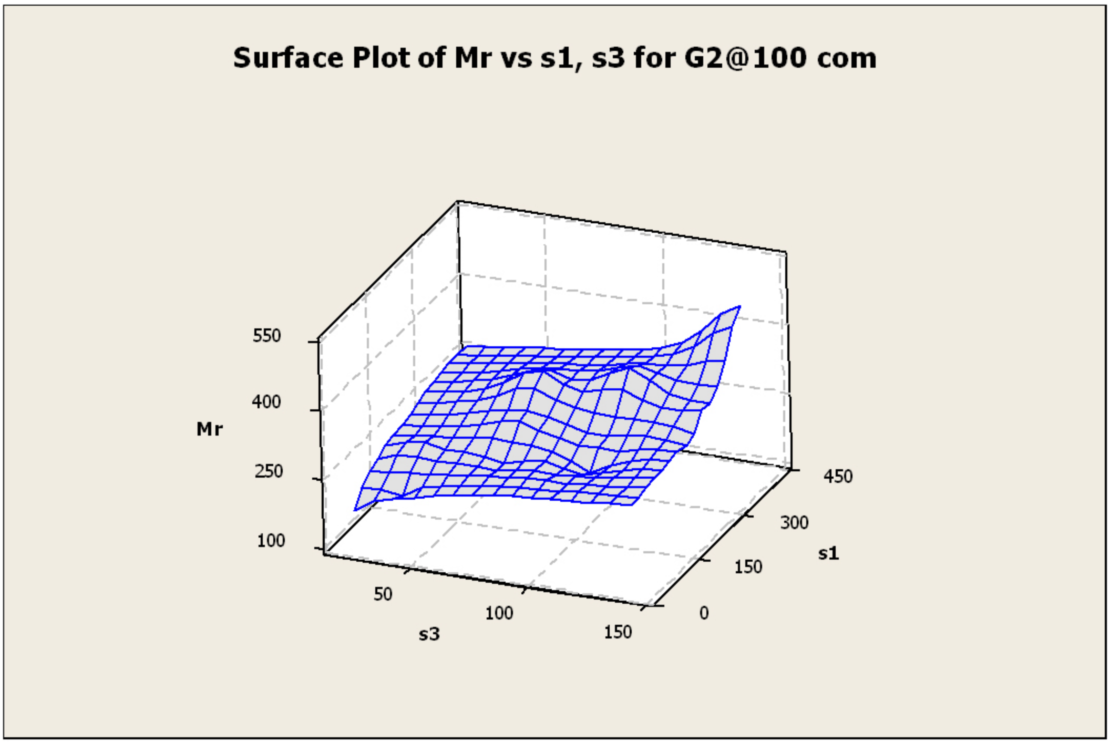


Figure 4.13 Resilient modulus vs stress state plot of G2 100% modified compaction

4.5.4 Influence of Gradation

From the relationship between resilient and related variables in equation 4.7 and 4.8, it can be explained that if the unbound crushed limestone samples of two different gradation G1 and G2 are prepared at the same percent moisture content and tested at the same stress condition, the coefficient k1, k2, k3 and k4 of G1 are higher than those of G2. So, it makes the resilient modulus of G1 higher than G2.

The table 4.22 presents the average resilient modulus in each test sequence of the Mr tests comparing between the average resilient modulus of G1 at 97% compaction and the average resilient modulus of G2 at 100% compaction. This data will be used for the paired t-tests. The paired t-test results are shown in table 4.23 – 4.25. The comparison results shown that, at 2.0% and 3.25% water content, the resilient modulus are different. And the Mr values of G2 are greater than G1. But at 4.5% water content, the paired t-test result shows no difference between G1 and G2 on the Mr values.

Table 4.22 Average resilient modulus of gradation G1 97% compaction and G2 100% compaction at specified moisture content

target %w	2.0		3.25		4.50	
Gradation	G1	G2	G1	G2	G1	G2
%compaction	97	100	97	100	97	100
sequence	Mr (MPa)	Mr (MPa)	Mr (MPa)	Mr (MPa)	Mr (MPa)	Mr (MPa)
1	150	185	139	174	117	111
2	162	213	157	202	140	141
3	193	243	179	232	158	166
4	174	219	160	200	129	132
5	212	263	195	247	168	176
6	251	296	222	279	193	202
7	228	272	215	253		

target %w	2.0		3.25		4.50	
Gradation	G1	G2	G1	G2	G1	G2
%compaction	97	100	97	100	97	100
sequence	Mr (MPa)	Mr (MPa)	Mr (MPa)	Mr (MPa)	Mr (MPa)	Mr (MPa)
8	309	334	270	324		
9	373	394	324	382		
10			246	259		
11			258	297		
12			352	390		
13			300	297		
14			312	342		
15			439	419		
No. of sample	4	3	5	3	3	3
average actual %w	2.15	1.95	3.27	3.13	4.18	4.19

Table 4.23 Result of statistical comparison of Mr averaged of sequence 1-15 between G1 97% compaction and G2 100% compaction at 2.0% moisture content.

t-Test: Paired Two Sample for Means		
2.0% W		
	G1	*G2*
Mean	228	269
Variance	5362.5	4240.4
Observations	9	9
Pearson Correlation	0.993	
Hypothesized Mean Difference	0.0	
df	8	
t Stat	-10.69	
P(T<=t) one-tail	0.00	
t Critical one-tail	1.86	
P(T<=t) two-tail	0.00	
t Critical two-tail	2.31	

Table 4.24 Result of statistical comparison of Mr averaged of sequence 1-15 between G1 97% compaction and G2 100% compaction at 3.25% moisture content.

t-Test: Paired Two Sample for Means		
3.25% W		
	G1	*G2*
Mean	251	286
Variance	6958.7	5415.1
Observations	15	15
Pearson Correlation	0.966	
Hypothesized Mean Difference	0.0	
df	14	
t Stat	-6.03	
P(T<=t) one-tail	0.00	
t Critical one-tail	1.76	
P(T<=t) two-tail	0.00	
t Critical two-tail	2.14	

Table 4.25 Result of statistical comparison of Mr averaged of sequence 1-15 between G1 97% compaction and G2 100% compaction at 4.5% moisture content.

t-Test: Paired Two Sample for Means		
4.5% W		
	G1	*G2*
Mean	151	155
Variance	772.51	1090.07
Observations	6	6
Pearson Correlation	#N/A	
Hypothesized Mean Difference	0	
df	5	
t Stat	-1.62	
P(T<=t) one-tail	0.08	
t Critical one-tail	2.02	
P(T<=t) two-tail	0.17	
t Critical two-tail	2.57	

Table 4.26 presents the average resilient modulus in each test sequence of the Mr tests comparing between the average resilient modulus of G1 at 103% compaction and the average resilient modulus of G2 at 100% compaction. The G1 at 103% compaction has the same dry density of 2.42 g/cm^3 as the G2 at 100% compaction This data will be used for the paired t-tests. The paired t-test results are shown in table 4.27 – 4.29. The comparison results shown that, at 2.0%, 3.25% and 4.5% water content, the null hypothesis will be rejected. That mean the G1 Mr values are different from G2 Mr values. From their mean values shown in Table 4.27 – 4.29, the Mr values of G1 are higher than those of G2.

Table 4.26 Average resilient modulus of gradation G1 103% compaction and G2 100% compaction at specified moisture content

target %w	2.0		3.25		4.50	
Gradation	G1	G2	G1	G2	G1	G2
%compaction	103	100	103	100	103	100
sequence	Mr (MPa)	Mr (MPa)	Mr (MPa)	Mr (MPa)	Mr (MPa)	Mr (MPa)
1	198	185	155	174	140	111
2	225	213	177	202	165	141
3	262	243	216	232	185	166
4	228	219	197	200	152	132
5	279	263	248	247	196	176
6	333	296	296	279	225	202
7	282	272	274	253		
8	355	334	353	324		
9	465	394	406	382		
10	329	261	285	259		
11	363	299	330	297		
12	475	419	433	390		
13	385	310	365	297		
14	417	359	399	342		
15			501	419		

target %w	2.0		3.25		4.50	
Gradation	G1	G2	G1	G2	G1	G2
%compaction	103	100	103	100	103	100
sequence	Mr (MPa)	Mr (MPa)	Mr (MPa)	Mr (MPa)	Mr (MPa)	Mr (MPa)
No. of sample	2	3	2	3	3	2
average actual %w	2.08	2.00	3.30	3.13	5.22	4.19

Table 4.27 Result of statistical comparison of Mr averaged of sequence 1-15 between G1 103% compaction and G2 100% compaction at 2.0% moisture content.

t-Test: Paired Two Sample for Means		
2.0%W		
	G1	*G2*
Mean	328	291
Variance	7721.3	4674.3
Observations	14	14
Pearson Correlation	0.974	
Hypothesized Mean Difference	0	
df	13	
t Stat	5.38	
P(T<=t) one-tail	0.00	
t Critical one-tail	1.77	
P(T<=t) two-tail	0.00	
t Critical two-tail	2.16	

Table 4.28 Result of statistical comparison of Mr averaged of sequence 1-15 between G1 103% compaction and G2 100% compaction at 3.25% moisture content.

t-Test: Paired Two Sample for Means		
3.25%W		
	G1	*G2*
Mean	309	286
Variance	10238.7	5417.1
Observations	15	15
Pearson Correlation	0.984	
Hypothesized Mean Difference	0	
df	14	
t Stat	2.77	
P(T<=t) one-tail	0.01	
t Critical one-tail	1.76	
P(T<=t) two-tail	0.02	
t Critical two-tail	2.14	

Table 4.29 Result of statistical comparison of Mr averaged of sequence 1-15 between G1 103% compaction and G2 100% compaction at 4.5% moisture content.

t-Test: Paired Two Sample for Means		
4.5% W		
	G1	*G2*
Mean	177	155
Variance	963.6	1090.1
Observations	6	6
Pearson Correlation	0.996	
Hypothesized Mean Difference	0	
df	5	
t Stat	15.44	
P(T<=t) one-tail	0.00	
t Critical one-tail	2.02	
P(T<=t) two-tail	0.00	
t Critical two-tail	2.57	

CHAPTER V

CONCLUSION AND RECOMMENDATIONS

5.1 Summary of Results and Findings

In this study, a crushed limestone is selected as a representative unbound granular material (UGM). Two gradations are selected in this study. A series of compacted cylindrical-shaped samples are prepared at varying five %moisture contents and two density levels for G1 gradation and varying three %moisture contents and one density level for G2 gradation to determining the resilient modulus of the UGM samples using the AASHTO T307 procedure. The findings of this research provide some understanding of the characteristic of the crushed limestone UGM and are greatly benefits to the road base construction and evaluation in the field as follows

1. Determination of the resilient modulus value is dependent of the stress state. The resilient modulus increases with the applied confining and deviatoric stresses level. Thus, defining the resilient modulus of a base material must be accompanied with the referred stress state. This may be important in the case of pavement deflection analysis that gives layer modulus results.
2. Resilient modulus increases significantly as the water content in the UGM reduces from the saturation side to the dry side. Though, the optimum moisture content is the easiest point to compact the UGM to the highest density, it does not provide the best resilient modulus at OMC condition. Perhaps, the UGM base layer should be left dried to reduce the moisture content for the best mechanistic performance of the constructed pavement.
3. From the Pearson's correlation statistical analysis, the compaction level has no significant influence to the resilient modulus at 99% confidential level.
4. The resilient modulus model given by Equation 2.2 is the constitutive equation developed by the NCHRP project 1-37A for the "Mechanistic-Empirical

Pavement Design Guide (MEPDG)". In this study, a modified model for predicting the resilient modulus is developed based on the regression analysis on test result data as follows.

$$M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{\mathrm{oct}}}{P_a} + 1\right)^{k_3} (w)^{k_4} \tag{4.5}$$

The regression analysis gives the k constants for crushed limestone aggregates as:

Fine-graded G1

k_1 = 0.436 k_2 = 0.173 k_3 = 1.079 k_4 = -0.331

Coarse-graded G2

k_1 = 0.338 k_2 = 0.103 k_3 = 1.053 k_4 = -0.425

where Pa is atmospheric pressure.

5.2 Recommendations

1. This research model is suitable in the laboratory only. In practical, the field construction should be control to near actual of OMC because moisture content is significant affect directly to Mr.
2. More sources of material should be selected to compare basic properties and the resilient modulus
3. The water content should vary less than this study due to the problem to compact the sample to the desired density. When sample is too dry, it cannot be compacted to the desired density especially when the over-energy compaction is selected.
4. Curing sample in plastic bag is required especially in dry sample to reduce the effect of water distribution in aggregate.

5. After the test is completed, the actual water content in a specimen is difficult to determine because some water is lost during the test or stuck onto the rubber membrane.
6. Sometimes, the vibratory compactor breaks the large-sized coarse aggregate during compaction. In the future, the compaction method should be tried with the gyratory compactor.

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Appendices

Appendix A

Basic Properties Test Data

Table A-1 Specific Gravity and Absorption of Coarse Aggregate

Sieve number	No.1/2 “		No. 3/8"	
Sample test repeated	1	3	1	2
A is weight of oven-dry sample in air (g)	356.6	479.8	326.6	388.8
B is weight of saturated surface-dry (SSD) (g)	357.7	481.3	327.6	390.2
C is weight of SSD sample in water (g)	226.2	303.5	206.8	245.6

Specific Gravity and Absorption of coarse Aggregate can be calculated as follows:				
1. The bulk Specific gravity = A/(B-C)	2.712	2.699	2.704	2.689
2. The bulk Specific gravity on saturated surface dry = B/(B-C)	2.720	2.707	2.712	2.698
3.The apparent specific gravity = A/(A-C)	2.734	2.722	2.726	2.715
4. The percentage of absorption = [(B-A)/A]*100	0.31	0.31	0.31	0.36

Table A-2 Specific Gravity and Absorption of fine Aggregate

Sieve number	No #40
A is weight of oven-dry sample in air (g)	372
B is weight of glass graduate filled with water(g)	660.5
C is weight of glass graduate with sample and water to calibration(g)	895.9
S is weight of saturated surface-dry sample(g)	374.9

Specific Gravity and Absorption of fine Aggregate can be calculated as follows:	
1.The bulk Specific gravity (Oven-dry basic) = A/(B+S-C)	2.667
2. The bulk Specific gravity on saturated surface -dry basic = S/(B+S-C)	2.687
3.The apparent Specific gravity = A/(B+A-C)	2.723
4. The percentage of absorption = [(S-A)/A]*100	0.780

Table A-3 Modified Compaction Test of Gradation G1

Project	Thesis chanpheng	Date	20.1.2013
Location	Saraburi	Tested by	Chanpheng
Soil Sample	Unbound granular materials		

Modified Compaction test for G1

Mold No	Mold No.1		Mold No.2		Mold No.3		Mold No.4	
Container No.	2.5%-1	2.5%-2	4.0%-1	4.0%-2	5.5%-1	5.5%-2	7.0%-1	7.0%-2
Weight of wet soil + container	373.8	376.1	402.5	417.1	346.7	369.1	565.4	526.9
Weight of dry soil + container	366.2	367.2	388.3	404.2	333.3	352.7	535.4	502.3
Weight of Water	7.6	8.9	14.2	12.9	13.4	16.4	30.0	24.6
Weight of container	42.2	39.9	40.7	40.2	39.0	34.7	40.3	38.7
Weight of dry soil	324.0	327.3	347.6	364.0	294.3	318.0	495.1	463.6
Water Content	2.3	2.7	4.1	3.5	4.6	5.2	6.1	5.3
Average water content	2.5		3.8		4.9		5.7	

Compaction Data

Mold No.	1.0	2.0	3.0	4.0
Number of blow/layer	56.0	56.0	56.0	56.0
Volume of Mold (cm^3)	2121.7	2121.7	2121.7	2121.7
Weight of Mold + Compacted soil	9122.5	9342.9	9508.4	9488.1
Weight of Mold	4278.3	4278.3	4278.6	4278.4
weight of compacted soil	4844.2	5064.6	5229.8	5209.7
Wet Density	2.28	2.39	2.46	2.46
Dry Density	2.23	2.30	2.35	2.32

Mold No.	1.0	2.0	3.0	4.0
Water content Assume (%)	2.50	4.00	5.50	7.00
Water content measure (%)	2.53	3.81	4.86	5.68

Compaction Curve

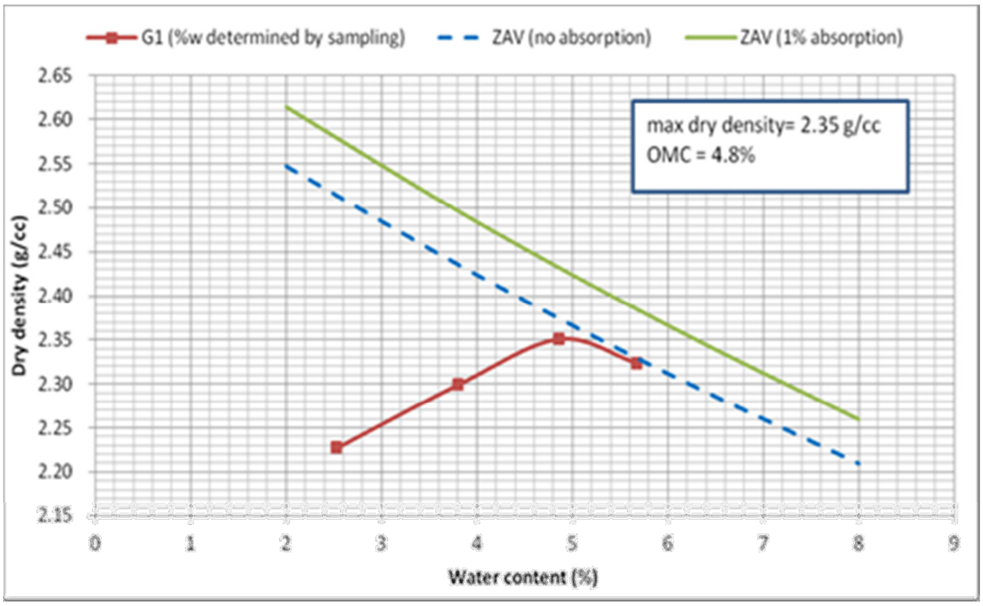


Table A-4 Modified Compaction Test of Gradation G2

Project	Thesis chanpheng	Date	20.1.2013
Location	Saraburi	Tested by	Chanpheng
Soil Sample	Unbound granular materials		

Modified Compaction test for G2

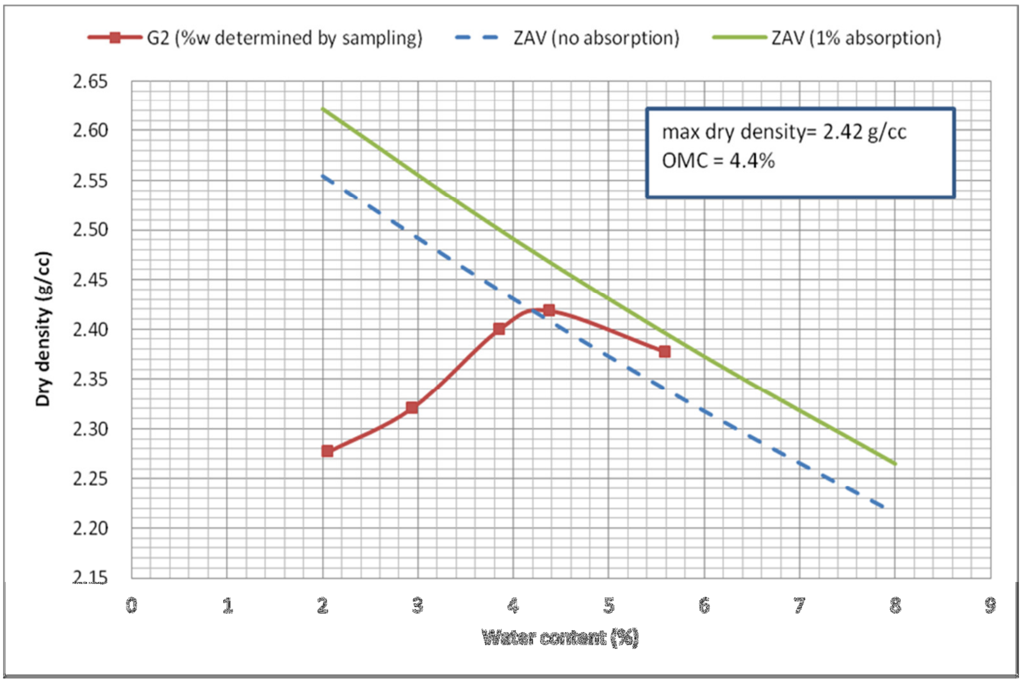
Mold No	Mold No.1		Mold No.2		Mold No.3		Mold No.4		Mold No.5	
Container No.	2%-1	2%-2	3%-1	3%-2	4%-1	4%-2	5%-1	5%-2	6%-1	6%-2
Weight of wet soil + container	325.8	359.1	513.8	549.4	373.1	343.6	663.1	697.6	461.7	404.0
Weight of dry soil + container	320.1	352.6	505.4	538.8	361.6	331.6	643.6	676.5	437.1	386.4
Weight of Water	5.7	6.5	8.4	10.6	11.5	12.0	19.5	21.0	24.6	17.6
Weight of container	42.1	39.9	199.6	199.8	40.7	40.2	202.6	193.2	38.9	34.7
Weight of dry soil	278.0	312.7	305.8	339.0	320.9	291.4	441.1	483.4	398.2	351.7
Water Content	2.05	2.08	2.76	3.12	3.58	4.12	4.41	4.35	6.18	5.00
Average water content	2.06		2.94		3.85		4.38		5.59	

Compaction Data

Mold No.	1	2	3	4	5
Number of blow/layer	56	56	56	56	56
Volume of Mold (cm^3)	2122.8	2126.3	2122.8	2126.3	2122.8
Weight of Mold + Compacted soil	9140.6	9340.4	9497.2	9628.5	9536.5
Weight of Mold	4207.6	4261.2	4207.7	4261.2	4207.7
weight of compacted soil	4933.0	5079.2	5289.5	5367.3	5328.8
Wet Density	2.32	2.39	2.49	2.52	2.51
Dry Density	2.28	2.32	2.40	2.42	2.38

Mold No.	1	2	3	4	5
Water content Assume (%)	2.00	3.00	4.00	5.00	6.00
Water content measure (%)	2.06	2.94	3.85	4.38	5.59

Compaction Curve



Appendix B

Resilient Modulus Test Data

Table B-1 Test Result of Gradation G1, 97% Compaction, 2.0% Moisture Content, Replicate 1

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	4/12/2012 11:11:29				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water2.0%_97%_1		Weight (g)	3569.2	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	199.5	198.1	199.7	199.1	0.883
Diameter (mm)	100.5	100.3	100.3	100.4	0.121
X-Section area (mm^2)	7910.6				
Loading program	Base/Subbase material (AASHTO TP46, T307)				
Load duration (ms)	100				
Cycle duration (ms)	1000				
Conditioning cycle count	20				
Cycles per sequence	20				
Axial Lvdt gauge length (mm)	200				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (μstrain)	Actuator MR (MPa)	Axial resilient (μstrain)	Axial MR (MPa)
0	93.21	10.10	103.40	749.02	124.45	447.58	208.26
1	18.63	2.06	20.70	166.90	111.60	121.65	153.12
2	37.02	4.12	20.70	436.02	84.92	229.57	161.28
3	55.55	6.22	20.70	582.10	95.43	321.69	172.68
4	30.96	3.37	34.50	256.02	120.93	183.04	169.14
5	61.92	6.67	34.50	609.18	101.65	337.36	183.54
6	93.13	10.09	34.50	765.81	121.61	441.57	210.90
7	61.45	7.15	68.90	592.40	103.73	328.52	187.05
8	124.29	13.67	68.89	894.46	138.96	550.00	225.99
9	184.87	22.09	68.89	1101.65	167.87	717.23	257.89
10	61.99	6.85	103.40	560.20	110.67	374.48	165.55
11	92.96	10.18	103.38	685.85	135.54	453.75	204.86
12	186.49	20.31	103.38	978.05	190.68	606.02	307.74
13	92.77	10.47	137.89	619.71	149.72	402.87	230.30
14	123.99	14.01	137.89	701.54	176.74	440.47	281.49
15	247.87	27.84	137.87	1110.03	223.30	674.65	367.41

Table B-2 Test Result of Gradation G1, 97% Compaction, 2.0% Moisture Content, Replicate 2

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	4/12/2012 11:11:29				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water 2.0%_97%_2		Weight (g)	3569.2	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	199.5	198.1	199.7	199.1	0.883
Diameter (mm)	100.5	100.3	100.3	100.4	0.121
X-Section area (mm^2)	7910.6				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	93.21	10.10	103.40	749.02	124.45	447.58	208.26
1	18.63	2.06	20.70	166.90	111.60	121.65	153.12
2	37.02	4.12	20.70	436.02	84.92	229.57	161.28
3	55.55	6.22	20.70	582.10	95.43	321.69	172.68
4	30.96	3.37	34.50	256.02	120.93	183.04	169.14
5	61.92	6.67	34.50	609.18	101.65	337.36	183.54
6	93.13	10.09	34.50	765.81	121.61	441.57	210.90
7	61.45	7.15	68.90	592.40	103.73	328.52	187.05
8	124.29	13.67	68.89	894.46	138.96	550.00	225.99
9	184.87	22.09	68.89	1101.65	167.87	717.23	257.89
10	61.99	6.85	103.40	560.20	110.67	374.48	165.55
11	92.96	10.18	103.38	685.85	135.54	453.75	204.86
12	186.49	20.31	103.38	978.05	190.68	606.02	307.74
13	92.77	10.47	137.89	619.71	149.72	402.87	230.30
14	123.99	14.01	137.89	701.54	176.74	440.47	281.49
15	247.87	27.84	137.87	1110.03	223.30	674.65	367.41

Table B-3 Test Result of Gradation G1, 97% Compaction, 2.0% Moisture Content, Replicate 3

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	4/12/2012 12:09:11				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water 2.0%_97%_3		Weight (g)	3558.7	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	200.6	200.4	201.1	200.7	0.378
Diameter (mm)	100.3	100.2	100.3	100.3	0.01
X-Section area (mm^2)	7893.3				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (μstrain)	Actuator MR (MPa)	Axial resilient (μstrain)	Axial MR (MPa)
0	93.04	10.33	103.38	723.45	128.60	390.03	238.56
1	18.56	2.16	20.70	177.96	104.32	131.63	141.04
2	36.89	4.40	20.70	329.76	111.86	235.19	156.84
3	55.48	6.37	20.70	564.87	98.22	323.28	171.63
4	30.85	3.53	34.50	258.67	119.28	182.28	169.27
5	61.59	7.03	34.50	592.55	103.94	331.37	185.87
6	92.92	10.34	34.50	765.99	121.31	426.70	217.78
7	61.89	6.91	68.90	590.98	104.72	306.15	202.16
8	124.00	13.82	68.89	886.21	139.93	490.02	253.06
9	185.93	20.73	68.89	1124.82	165.30	612.69	303.47
10	61.85	6.87	103.40	654.99	94.43	322.20	191.96
11	92.95	10.26	103.39	824.62	112.72	422.52	219.99
12	185.95	20.75	103.40	1131.21	164.38	596.08	311.96
13	92.91	10.37	137.90	849.13	109.42	436.35	212.93
14	123.80	13.89	137.89	943.09	131.27	489.15	253.08
15	248.04	27.51	137.91	1347.55	184.07	759.84	326.45

Table B-4 Test Result of Gradation G1, 97% Compaction, 2.0% Moisture Content, Replicate 4

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	7/12/2012 13:10:33				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water 2.0%_97%_4		Weight (g)	3596.2	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	199.8	200.4	199.3	199.8	0.545
Diameter (mm)	100.3	100	100.3	100.2	0.174
X-Section area (mm^2)	7885.4				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	93.32	10.06	103.39	446.65	208.93	290.81	320.89
1	18.54	2.12	20.69	122.85	150.97	80.70	229.79
2	37.33	4.05	20.70	232.26	160.74	155.64	239.87
3	55.83	6.21	20.70	316.93	176.16	212.74	262.44
4	31.06	3.45	34.50	183.73	169.07	117.80	263.68
5	61.81	6.86	34.50	329.43	187.62	216.77	285.14
6	92.90	10.37	34.50	459.15	202.33	304.92	304.65
7	61.91	6.83	68.90	306.42	202.06	196.58	314.96
8	124.04	13.81	68.89	565.16	219.48	369.62	335.60
9	186.05	20.68	68.90	763.33	243.74	481.16	386.68
10	61.86	6.95	103.40	319.03	193.90	205.70	300.72
11	92.98	10.36	103.39	450.13	206.56	295.82	314.31
12	186.04	20.69	103.39	739.80	251.47	454.90	408.97
13	93.12	10.23	137.89	439.20	212.01	283.46	328.50
14	124.10	13.72	137.90	542.14	228.91	343.82	360.95
15	248.27	27.52	137.89	904.63	274.44	529.51	468.86

Table B-5 Test Result of Gradation G1, 97% Compaction, 3.25% Moisture Content, Replicate 1

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	29/11/2012 14:10:52				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water 3.25%_97%_1		Weight (g)	3484.4	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	198.7	197.3	198.6	198.2	0.791
Diameter (mm)	100.3	100.4	100.4	100.4	0.049
X-Section area (mm^2)	7911.7				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (μstrain)	Actuator MR (MPa)	Axial resilient (μstrain)	Axial MR (MPa)
0	92.99	10.30	103.37	499.29	186.26	318.02	292.43
1	18.67	2.03	20.69	203.69	91.66	142.43	131.08
2	37.24	4.11	20.70	349.01	106.70	254.31	146.44
3	55.87	6.21	20.70	456.78	122.31	329.62	169.49
4	30.95	3.49	34.50	286.99	107.85	204.37	151.45
5	61.91	6.91	34.49	470.06	131.71	335.17	184.72
6	93.12	10.23	34.49	615.08	151.40	434.64	214.25
7	61.93	6.88	68.89	411.96	150.32	283.14	218.72
8	124.01	13.77	68.89	704.53	176.02	467.31	265.37
9	186.02	20.70	68.89	946.31	196.57	600.56	309.74
10	62.31	6.49	103.39	380.63	163.71	250.44	248.80
11	93.41	9.97	103.39	554.93	168.33	374.17	249.65
12	185.68	20.82	103.37	914.19	203.11	570.47	325.49
13	93.30	9.95	137.90	516.81	180.53	337.69	276.30
14	124.38	13.39	137.89	660.54	188.30	426.88	291.36
15	247.89	27.77	137.87	1092.01	227.00	646.10	383.68

Table B-6 Test Result of Gradation G1, 97% Compaction, 3.25% Moisture Content, Replicate 2

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	29/11/2012 14:59:25				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water 3.25%_97%_2		Weight (g)	3647.3	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	200.3	200.1	200.1	200.1	0.102
Diameter (mm)	100.1	100.3	100.3	100.2	0.101
X-Section area (mm^2)	7889.6				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (μstrain)	Actuator MR (MPa)	Axial resilient (μstrain)	Axial MR (MPa)
0	92.97	10.39	103.39	504.62	184.24	338.44	274.71
1	18.48	2.12	20.69	212.35	87.01	164.93	112.02
2	37.15	4.04	20.70	364.20	102.00	286.06	129.87
3	55.94	6.13	20.70	475.94	117.54	368.24	151.91
4	30.89	3.50	34.50	292.09	105.75	223.59	138.14
5	61.98	6.80	34.50	475.96	130.21	361.05	171.65
6	93.27	10.02	34.50	617.10	151.14	452.13	206.29
7	61.90	6.78	68.90	428.61	144.43	313.72	197.32
8	124.26	13.55	68.90	699.64	177.61	477.13	260.44
9	186.27	20.39	68.90	918.43	202.81	580.52	320.87
10	61.92	6.92	103.39	383.56	161.44	264.25	234.34
11	92.98	10.31	103.39	564.92	164.59	389.57	238.68
12	186.32	20.46	103.39	884.80	210.59	542.81	343.26
13	93.28	10.17	137.89	517.14	180.38	337.40	276.48
14	124.21	13.69	137.89	655.06	189.61	422.43	294.03
15	248.43	27.31	137.89	1027.06	241.89	592.98	418.96

Table B-7 Test Result of Gradation G1, 97% Compaction, 3.25% Moisture Content, Replicate 3

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	29/11/2012 15:49:23				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water 3.25%_97%_3		Weight (g)	3638.2	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	199.5	199.5	199.9	199.6	0.231
Diameter (mm)	100	100.3	100.2	100.2	0.153
X-Section area (mm^2)	7880.2				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (μstrain)	Actuator MR (MPa)	Axial resilient (μstrain)	Axial MR (MPa)
0	93.16	10.12	103.39	569.76	163.52	375.57	248.07
1	18.53	2.09	20.70	183.92	100.74	136.66	135.57
2	37.26	4.06	20.70	329.56	113.07	246.90	150.92
3	55.78	6.34	20.70	444.01	125.63	326.64	170.77
4	30.91	3.49	34.50	264.83	116.70	194.04	159.28
5	61.82	6.95	34.50	457.90	135.00	328.74	188.04
6	92.94	10.31	34.49	623.85	148.98	441.17	210.67
7	61.99	6.88	68.90	421.11	147.21	291.03	213.01
8	124.01	13.75	68.89	716.25	173.14	482.86	256.82
9	186.06	20.62	68.90	907.15	205.10	587.15	316.88
10	61.87	6.87	103.39	406.21	152.30	269.15	229.86
11	92.92	10.34	103.39	569.93	163.03	380.80	244.00
12	186.05	20.72	103.39	867.10	214.57	541.20	343.77
13	93.08	10.25	137.89	534.50	174.14	341.49	272.56
14	124.17	13.69	137.89	652.50	190.29	415.02	299.18
15	248.34	27.39	137.89	1004.80	247.15	590.04	420.89

Table B-8 Test Result of Gradation G1, 97% Compaction, 3.25% Moisture Content, Replicate 4

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	8/2/2013 12:03:40				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water 3.25%_97%_4		Weight (g)	3694.3	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	196.5	197	197	196.8	0.289
Diameter (mm)	100	100	100	100	0
X-Section area (mm^2)	7854				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (μstrain)	Actuator MR (MPa)	Axial resilient (μstrain)	Axial MR (MPa)
0	92.99	10.36	103.39	492.56	188.80	331.06	280.90
1	18.54	2.11	20.70	163.29	113.54	118.60	156.31
2	37.23	4.05	20.70	278.50	133.70	200.02	186.16
3	56.11	5.98	20.69	369.06	152.03	259.66	216.09
4	30.94	3.50	34.50	238.99	129.48	172.49	179.39
5	61.92	6.95	34.50	386.73	160.12	266.78	232.12
6	93.07	10.30	34.50	516.40	180.23	351.49	264.79
7	61.92	6.90	68.90	387.47	159.80	269.36	229.86
8	123.96	13.78	68.90	603.69	205.33	399.80	310.04
9	185.86	20.71	68.90	789.02	235.56	498.60	372.77
10	61.93	6.88	103.39	384.50	161.06	269.54	229.74
11	92.91	10.34	103.39	510.96	181.83	348.88	266.29
12	186.04	20.67	103.39	762.64	243.95	472.10	394.07
13	93.06	10.29	137.89	495.99	187.62	334.59	278.13
14	124.02	13.78	137.90	584.83	212.07	381.13	325.42
15	248.01	27.56	137.89	908.15	273.09	539.50	459.70

Table B-9 Test Result of Gradation G1, 97% Compaction, 3.25% Moisture Content, Replicate 5

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	8/2/2013 13:12:50				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water 3.25%_97%_5		Weight (g)	3868.3	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	197	197.5	197.5	197.3	0.289
Diameter (mm)	100	100	100	100	0
X-Section area (mm^2)	7854				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	92.80	10.37	103.38	508.85	182.38	350.20	265.01
1	18.76	1.94	20.70	170.81	109.85	124.14	151.14
2	37.43	3.85	20.69	299.44	124.99	217.94	171.73
3	56.10	5.88	20.69	397.55	141.12	287.01	195.48
4	31.20	3.24	34.50	252.41	123.59	184.48	169.10
5	62.25	6.57	34.50	416.42	149.48	296.26	210.11
6	92.99	10.32	34.50	555.01	167.55	394.80	235.54
7	62.12	6.80	68.89	404.93	153.40	290.43	213.87
8	124.08	13.64	68.89	655.93	189.16	452.97	273.91
9	185.13	21.48	68.88	875.76	211.39	577.34	320.66
10	61.95	6.90	103.38	404.31	153.22	289.45	214.01
11	92.93	10.34	103.38	529.31	175.56	371.51	250.13
12	186.00	20.71	103.38	798.02	233.08	507.16	366.76
13	93.10	10.26	137.90	493.66	188.59	337.44	275.91
14	124.02	13.73	137.89	573.85	216.12	374.50	331.16
15	248.35	27.31	137.87	917.55	270.67	544.47	456.13

Table B-10 Test Result of Gradation G1, 97% Compaction, 4.5% Moisture Content, Replicate 2

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	30/11/2012 12:10:16				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water 4.5%_97%_2		Weight (g)	3694.4	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	198.2	196.8	196.3	197.1	0.979
Diameter (mm)	100	99.8	100	99.9	0.104
X-Section area (mm^2)	7844.6				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (μstrain)	Actuator MR (MPa)	Axial resilient (μstrain)	Axial MR (MPa)
0	93.22	10.13	103.39	752.86	123.83	543.90	171.42
1	18.58	2.03	20.70	244.86	75.87	195.16	95.19
2	37.19	4.13	20.70	413.42	89.95	325.44	114.26
3	56.08	5.98	20.70	558.83	100.36	425.55	131.79
4	30.83	3.56	34.50	353.83	87.14	279.99	110.12
5	62.24	6.52	34.50	579.20	107.47	437.95	142.12
6	93.01	10.35	34.49	790.55	117.66	584.31	159.19
7	61.88	6.91	68.89	606.82	101.98	463.27	133.58
8	123.51	14.35	68.88	908.11	136.01	653.40	189.03
9	185.83	20.94	68.89	1216.25	152.79	852.22	218.06
10	61.76	7.14	103.41	715.61	86.31	536.85	115.05
11	92.95	10.33	103.39	851.03	109.22	604.94	153.66
12	185.29	21.38	103.39	1173.13	157.96	791.60	234.10
13	92.89	10.55	137.89	868.75	106.94	642.40	144.63
14	123.97	13.79	137.88	906.52	136.75	634.95	195.25
15	247.31	28.41	137.88	1293.84	191.15	858.73	288.00

Table B-11 Test Result of Gradation G1, 97% Compaction, 4.5% Moisture Content, Replicate 3

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	30/11/2012 13:51:27				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water 4.5%_97%_3		Weight (g)	3682.6	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	199	199.5	199.1	199.2	0.282
Diameter (mm)	100.2	100	100	100.1	0.11
X-Section area (mm^2)	7863.9				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	92.73	10.50	103.40	595.55	155.71	408.97	226.76
1	18.60	2.03	20.70	193.32	96.22	149.87	124.11
2	37.17	4.13	20.70	335.51	110.78	257.44	144.37
3	55.80	6.17	20.69	448.48	124.41	337.25	165.45
4	30.85	3.60	34.50	288.72	106.84	221.79	139.08
5	61.76	6.90	34.50	465.60	132.65	343.37	179.86
6	93.23	10.11	34.50	628.24	148.39	447.59	208.29
7	61.88	6.86	68.90	482.79	128.17	356.69	173.48
8	123.97	13.78	68.90	751.56	164.95	501.06	247.41
9	186.39	20.31	68.91	1046.11	178.18	695.50	268.00
10	61.55	7.25	103.40	595.56	103.34	447.96	137.39
11	93.02	10.30	103.41	708.05	131.39	509.49	182.60
12	186.48	20.27	103.41	1053.28	177.05	689.50	270.45
13	92.72	10.63	137.91	792.03	117.07	578.19	160.38
14	123.91	13.80	137.90	828.31	149.60	562.46	220.32
15	248.61	27.05	137.92	1309.51	189.85	865.80	287.17

Table B-12 Test Result of Gradation G1, 97% Compaction, 4.5% Moisture Content, Replicate 4

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	8/2/2013 14:17:14				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water 4.5%_97%_4		Weight (g)	3728.2	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	195	195	195.2	195.1	0.115
Diameter (mm)	100	100	100	100	0
X-Section area (mm^2)	7854				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				

Modulus test Mean and Std. Deviation data:

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	93.21	10.06	103.38	568.02	164.10	400.11	232.96
1	18.60	2.06	20.70	189.13	98.33	139.83	132.99
2	37.11	4.19	20.70	314.45	118.00	230.07	161.28
3	55.73	6.26	20.69	425.88	130.85	315.60	176.57
4	30.94	3.44	34.49	296.97	104.19	225.57	137.16
5	61.93	6.95	34.49	459.85	134.68	338.45	182.99
6	92.91	10.35	34.49	611.29	151.99	438.61	211.82
7	61.91	6.91	68.89	477.67	129.61	351.91	175.92
8	124.01	13.78	68.89	707.30	175.33	487.61	254.32
9	185.91	20.72	68.89	917.64	202.59	606.24	306.66
10	62.18	6.69	103.40	478.80	129.86	350.50	177.40
11	93.15	10.15	103.37	586.28	158.89	414.44	224.77
12	186.11	20.59	103.37	890.40	209.02	578.13	321.91
13	93.07	10.19	137.90	590.03	157.74	416.06	223.69
14	124.10	13.71	137.90	670.56	185.08	451.85	274.66
15	248.07	27.63	137.90	1109.87	223.52	705.65	351.55

Table B-13 Test Result of Gradation G1, 97% Compaction, 5.5% Moisture Content, Replicate 1

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	30/11/2012 14:36:55				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water 5.5%_97%_1		Weight (g)	3649.6	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	197.2	197.1	197.8	197.4	0.396
Diameter (mm)	100	99.2	99.5	99.6	0.388
X-Section area (mm^2)	7789.2				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				

Modulus test Mean and Std. Deviation data:

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	93.17	10.17	103.40	775.27	120.17	568.07	164.01
1	18.68	2.01	20.70	244.76	76.33	199.93	93.44
2	37.26	4.02	20.70	413.84	90.04	324.13	114.96
3	55.95	6.06	20.70	548.75	101.96	429.30	130.33
4	31.08	3.36	34.50	355.05	87.54	282.55	110.01
5	62.19	6.61	34.50	566.47	109.79	439.35	141.56
6	93.02	10.63	34.51	893.12	104.17	731.46	127.20
7	62.27	6.61	68.91	771.29	80.74	651.56	95.58
8	124.31	13.59	68.92	1119.87	111.00	873.55	142.31
9							
10							
11							
12							
13							
14							
15							

Table B-14 Test Result of Gradation G1, 97% Compaction, 5.5% Moisture Content, Replicate 2

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	4/12/2012 12:53:03				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water 5.5%_97%_2		Weight (g)	3652.1	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	194.1	194.9	195.9	195	0.933
Diameter (mm)	99.7	99.8	99.8	99.8	0.09
X-Section area (mm^2)	7816.9				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (μstrain)	Actuator MR (MPa)	Axial resilient (μstrain)	Axial MR (MPa)
0	93.16	10.22	103.38	1160.72	80.26	591.14	157.60
1	18.62	2.01	20.69	250.80	74.26	198.82	93.68
2	37.53	3.76	20.69	448.21	83.73	335.12	111.99
3	56.01	5.80	20.69	886.61	63.18	467.51	119.81
4	31.30	3.16	34.50	394.87	79.27	309.29	101.20
5	61.91	6.59	34.50	863.46	71.71	477.06	129.79
6	93.09	10.02	34.50	1022.48	91.05	594.73	156.53
7	61.99	6.74	68.89	808.44	76.68	477.35	129.86
8	123.71	13.77	68.90	1008.64	122.67	600.75	205.95
9							
10							
11							
12							
13							
14							
15							

Table B-15 Test Result of Gradation G1, 103% Compaction, 2.0% Moisture Content, Replicate 1

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	14/1/2013 9:29:24				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water2.0%_103%_1		Weight (g)	3651.8	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	200	200.4	200	200.2	0.26
Diameter (mm)	100.5	100.3	100.2	100.3	0.153
X-Section area (mm^2)	7906.4				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	93.23	10.23	103.38	463.74	201.04	308.54	302.17
1	18.43	2.18	20.69	132.37	139.27	90.89	202.79
2	37.00	4.32	20.69	239.65	154.40	168.33	219.81
3	55.60	6.39	20.69	329.09	168.96	229.12	242.68
4	30.92	3.51	34.50	199.06	155.33	136.11	227.17
5	61.82	7.03	34.49	351.79	175.72	242.27	255.15
6	92.92	10.40	34.49	477.53	194.59	322.15	288.43
7	61.95	6.94	68.89	347.50	178.28	238.04	260.27
8	124.15	13.69	68.89	588.52	210.96	387.37	320.51
9	186.02	20.68	68.88	782.70	237.66	495.64	375.31
10	62.00	6.90	103.39	308.04	201.26	196.08	316.17
11	93.04	10.30	103.39	452.11	205.79	293.05	317.49
12	186.04	20.71	103.37	755.23	246.33	474.03	392.45
13	93.02	10.31	137.89	423.51	219.63	269.20	345.53
14	123.96	13.86	137.89	546.31	226.90	348.39	355.79
15	248.02	27.67	137.89	919.32	269.78	552.41	448.98

Table B-16 Test Result of Gradation G1, 103% Compaction, 2.0% Moisture Content, Replicate 2

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	14/1/2013 11:29:11				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water2.0%_103%_2		Weight (g)	3693.4	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	202.1	201.1	200	201.1	1.045
Diameter (mm)	100.1	100	100.1	100.1	0.01
X-Section area (mm^2)	7863.4				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (μstrain)	Actuator MR (MPa)	Axial resilient (μstrain)	Axial MR (MPa)
0	93.09	10.29	103.39	458.64	202.97	296.40	314.07
1	18.51	2.16	20.69	126.63	146.15	82.75	223.63
2	37.16	4.16	20.70	234.74	158.30	155.37	239.16
3	55.78	6.29	20.69	324.53	171.89	217.42	256.56
4	30.93	3.55	34.50	195.70	158.04	128.33	241.01
5	61.90	6.98	34.49	349.85	176.95	233.51	265.10
6	92.85	10.51	34.49	473.14	196.25	306.46	302.98
7	61.85	6.91	68.89	342.81	180.41	227.35	272.03
8	123.89	14.00	68.89	589.01	210.33	376.50	329.05
9	186.09	20.55	68.89	793.13	234.62	492.29	378.01
10	61.95	6.88	103.40	336.63	184.03	224.27	276.22
11	92.92	10.46	103.39	458.99	202.45	296.84	313.05
12	185.89	20.80	103.39	753.08	246.84	452.77	410.56
13	92.87	10.34	137.89	447.74	207.43	284.34	326.63
14	123.61	14.18	137.89	545.63	226.56	336.75	367.08
15	248.43	27.18	137.89	922.93	269.17	530.66	468.15

Table B-17 Test Result of Gradation G1, 103% Compaction, 3.25% Moisture Content, Replicate 2

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	14/1/2013 13:59:56				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water3.25%_103%_2		Weight (g)	3891.1	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	200	200.1	201	200.4	0.564
Diameter (mm)	100	100.1	100	100	0.015
X-Section area (mm^2)	7860.8				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	92.96	10.29	103.39	431.87	215.24	265.19	350.54
1	18.69	2.02	20.70	167.05	111.85	123.76	150.98
2	37.32	4.07	20.69	290.46	128.49	213.19	175.06
3	56.00	6.17	20.70	373.22	150.04	265.26	211.11
4	31.07	3.39	34.50	219.01	141.89	151.99	204.46
5	62.14	6.84	34.49	367.96	168.87	251.51	247.04
6	92.90	10.38	34.49	502.68	184.82	335.18	277.17
7	62.05	6.90	68.90	340.38	182.30	224.03	276.97
8	123.85	13.89	68.89	577.73	214.37	359.82	344.19
9	186.08	20.52	68.88	787.35	236.34	470.92	395.15
10	62.09	6.82	103.39	323.66	191.84	206.76	300.29
11	93.03	10.27	103.39	448.08	207.62	278.47	334.07
12	186.15	20.54	103.39	743.12	250.50	428.29	434.65
13	92.99	10.27	137.89	419.25	221.79	252.99	367.56
14	123.93	13.84	137.89	519.81	238.42	303.45	408.41
15	248.12	27.48	137.89	901.40	275.26	488.51	507.90

Table B-18 Test Result of Gradation G1, 103% Compaction, 3.25% Moisture Content, Replicate 3

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	14/1/2013 15:05:31				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water3.25%_103%_3		Weight (g)	3887.4	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	202	203.1	201.1	202	1
Diameter (mm)	100	100	100	100	0.012
X-Section area (mm^2)	7860.8				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	93.27	9.97	103.39	408.29	228.45	256.46	363.70
1	18.74	1.94	20.69	140.39	133.45	100.00	187.35
2	37.33	3.94	20.69	253.16	147.47	179.46	208.02
3	56.07	6.02	20.70	336.26	166.74	234.33	239.27
4	31.10	3.33	34.50	200.70	154.96	136.73	227.45
5	62.08	6.69	34.49	339.89	182.66	231.11	268.63
6	93.24	10.12	34.49	470.76	198.06	318.58	292.68
7	62.14	6.64	68.89	319.62	194.42	209.13	297.12
8	124.15	13.66	68.89	552.43	224.73	357.66	347.11
9	186.10	20.64	68.88	752.01	247.48	471.52	394.69
10	62.37	6.57	103.39	309.77	201.33	199.33	312.89
11	93.30	9.99	103.39	431.36	216.30	276.59	337.33
12	186.09	20.68	103.37	711.52	261.54	427.80	434.99
13	93.46	9.83	137.89	398.03	234.79	241.86	386.40
14	124.31	13.48	137.89	501.97	247.65	300.81	413.26
15	248.26	27.48	137.89	859.21	288.94	491.13	505.49

Table B-19 Test Result of Gradation G1, 103% Compaction, 4.5% Moisture Content, Replicate 1

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	10/1/2013 10:13:43				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water4.5%_103%_1		Weight (g)	3951.2	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	200	200.1	200	200	0.029
Diameter (mm)	100	100.5	100	100.2	0.289
X-Section area (mm^2)	7880.2				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	93.12	10.09	103.38	602.92	154.45	442.68	210.36
1	18.55	2.08	20.70	194.22	95.49	153.21	121.05
2	36.59	4.74	20.70	326.55	112.05	252.40	144.97
3	54.75	7.37	20.70	440.78	124.22	339.56	161.25
4	30.18	4.30	34.49	294.84	102.37	232.59	129.75
5	60.85	8.02	34.49	467.14	130.26	357.81	170.07
6	91.60	11.67	34.49	607.63	150.75	453.12	202.16
7	61.62	7.29	68.89	478.49	128.78	366.22	168.26
8	123.20	14.69	68.89	731.99	168.31	529.70	232.58
9	184.65	21.94	68.88	962.58	191.83	660.45	279.58
10	61.95	6.89	103.39	433.04	143.05	320.56	193.25
11	93.02	10.31	103.37	540.83	171.99	382.09	243.44
12	185.94	20.68	103.37	843.82	220.36	547.02	339.92
13	92.92	10.33	137.90	544.35	170.70	387.23	239.96
14	124.06	13.78	137.90	627.75	197.63	424.41	292.32
15	248.10	27.43	137.87	1034.19	239.90	633.46	391.67

Table B-20 Test Result of Gradation G1, 103% Compaction, 4.5% Moisture Content, Replicate 2

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	10/1/2013 11:08:17				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water4.5%_103%_2		Weight (g)	3939.6	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	198	199	198.5	198.5	0.5
Diameter (mm)	100	99.9	100	100	0.058
X-Section area (mm^2)	7848.7				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				

Modulus test Mean and Std. Deviation data:

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	93.27	10.04	103.39	510.00	182.88	357.07	261.21
1	18.65	1.97	20.70	165.93	112.41	122.77	151.93
2	37.43	3.89	20.69	281.32	133.07	206.50	181.28
3	56.06	5.95	20.69	379.94	147.56	276.77	202.56
4	31.00	3.41	34.49	249.29	124.34	185.58	167.01
5	62.20	6.56	34.49	403.61	154.10	292.73	212.47
6	93.39	9.98	34.49	549.42	169.98	392.59	237.88
7	62.18	6.65	68.89	416.41	149.32	306.48	202.89
8	124.24	13.63	68.89	660.80	188.01	459.79	270.21
9	186.42	20.45	68.89	873.56	213.40	581.35	320.67
10	62.18	6.75	103.40	412.38	150.79	304.47	204.24
11	93.31	10.05	103.39	548.05	170.27	393.03	237.42
12	186.29	20.32	103.38	832.10	223.88	543.11	343.01
13	93.33	10.11	137.90	518.16	180.12	366.28	254.81
14	124.27	13.55	137.90	622.15	199.75	425.57	292.02
15	248.58	27.18	137.89	992.26	250.52	607.55	409.15

Table B-21 Test Result of Gradation G1, 103% Compaction, 4.5% Moisture Content, Replicate 3

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	10/1/2013 12:13:09				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water4.5%_103%_3		Weight (g)	3939.6	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	198.5	198.6	199.5	198.9	0.551
Diameter (mm)	100	100	100	100	0.029
X-Section area (mm^2)	7856.6				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (μstrain)	Actuator MR (MPa)	Axial resilient (μstrain)	Axial MR (MPa)
0	93.19	10.16	103.37	523.06	178.16	366.49	254.27
1	18.53	2.07	20.70	166.95	111.01	126.05	147.01
2	37.26	4.06	20.70	290.00	128.47	219.55	169.70
3	55.89	6.17	20.69	388.04	144.04	290.59	192.35
4	30.91	3.41	34.50	252.57	122.38	192.63	160.46
5	62.00	6.80	34.50	409.14	151.54	302.04	205.28
6	92.95	10.27	34.49	551.45	168.56	396.92	234.19
7	62.05	6.84	68.89	411.55	150.77	303.61	204.37
8	124.11	13.73	68.89	652.08	190.33	445.47	278.61
9	186.03	20.63	68.89	864.28	215.25	562.95	330.46
10	62.16	6.76	103.40	411.09	151.20	299.70	207.40
11	93.29	10.13	103.40	529.91	176.04	371.88	250.85
12	186.08	20.67	103.39	821.50	226.51	520.59	357.44
13	93.28	10.06	137.89	517.98	180.08	355.42	262.44
14	124.35	13.52	137.89	609.78	203.93	398.69	311.91
15	248.21	27.43	137.89	1002.07	247.70	607.87	408.33

Table B-22 Test Result of Gradation G1, 103% Compaction, 5.5% Moisture Content, Replicate 1

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	10/1/2013 13:19:29				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water5.5%_103%_1		Weight (g)	3951.3	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	197	197.5	197.5	197.3	0.289
Diameter (mm)	99.5	100	100	99.8	0.289
X-Section area (mm^2)	7856.6				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (μstrain)	Actuator MR (MPa)	Axial resilient (μstrain)	Axial MR (MPa)
0	93.11	10.21	103.38	603.40	154.31	429.46	216.81
1	18.57	2.09	20.69	186.20	99.72	141.32	131.39
2	37.25	4.08	20.69	320.42	116.25	239.45	155.56
3	55.80	6.24	20.69	429.85	129.82	320.58	174.07
4	30.91	3.58	34.50	297.36	103.96	231.24	133.69
5	62.05	6.81	34.49	463.46	133.89	342.08	181.39
6	93.19	10.17	34.49	620.75	150.13	451.43	206.44
7	61.92	6.93	68.89	495.06	125.08	375.33	164.98
8	124.10	13.79	68.89	750.69	165.32	532.73	232.95
9	186.25	20.49	68.89	960.27	193.96	666.52	279.44
10	61.95	6.79	103.39	478.48	129.47	367.75	168.45
11	93.13	10.17	103.37	583.94	159.48	425.32	218.96
12	186.15	20.49	103.38	958.84	194.14	660.83	281.70
13	93.03	10.28	137.88	588.03	158.20	424.71	219.04
14	124.27	13.63	137.88	706.93	175.78	492.37	252.38
15	0.04	53.93	137.89	0.00	0.00	0.78	48.12

Table B-23 Test Result of Gradation G1, 103% Compaction, 5.5% Moisture Content, Replicate 2

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	10/1/2013 14:25:12				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water5.5%_103%_2		Weight (g)	3963.6	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	197.5	197.5	198.5	197.8	0.577
Diameter (mm)	100	100	100	100	0.029
X-Section area (mm^2)	7856.6				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (μstrain)	Actuator MR (MPa)	Axial resilient (μstrain)	Axial MR (MPa)
0	93.32	10.08	103.39	533.77	174.82	373.14	250.08
1	18.59	2.06	20.69	169.25	109.83	126.62	146.81
2	37.21	4.11	20.70	292.45	127.23	216.99	171.48
3	55.71	6.18	20.70	398.36	139.85	294.90	188.92
4	30.94	3.49	34.50	262.95	117.68	196.58	157.41
5	61.90	6.84	34.50	423.93	146.02	311.22	198.90
6	93.13	10.23	34.50	584.10	159.44	427.42	217.89
7	62.09	6.82	68.89	426.29	145.66	314.91	197.18
8	124.10	13.74	68.89	702.49	176.66	491.98	252.25
9							
10							
11							
12							
13							
14							
15							

Table B-24 Test Result of Gradation G1, 103% Compaction, 5.5% Moisture Content, Replicate 3

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	10/1/2013 15:34:12				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G1_Water5.5%_103%_3		Weight (g)	3976.3	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	200	199	198	199	1
Diameter (mm)	100	99.9	100	100	0.058
X-Section area (mm^2)	7848.7				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	92.87	10.42	103.38	617.55	150.38	471.98	196.76
1	18.65	1.97	20.70	203.07	91.86	163.18	114.31
2	37.46	3.84	20.70	330.86	113.21	264.64	141.54
3	56.04	5.92	20.69	451.14	124.21	353.58	158.49
4	31.20	3.26	34.50	298.51	104.51	237.89	131.15
5	62.41	6.48	34.49	479.70	130.11	374.60	166.62
6	93.54	9.81	34.49	670.47	139.52	527.56	177.31
7	61.92	6.89	68.89	498.69	124.16	400.87	154.45
8	124.65	13.18	68.89	826.48	150.82	637.70	195.47
9	184.79	21.97	68.90	1129.44	163.61	837.13	220.74
10	62.28	6.60	103.39	548.60	113.53	444.63	140.07
11	93.06	10.25	103.38	634.79	146.59	480.41	193.70
12	185.15	21.48	103.38	1060.72	174.55	282.91	657.16
13	93.08	10.30	137.88	669.47	139.04	219.01	425.06
14	124.06	13.71	137.88	721.69	171.90	191.14	649.06
15							

Table B-25 Test Result of Gradation G2, 100% Compaction, 2.0% Moisture Content, Replicate 1

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	20/2/2013 9:19:41				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G2_Water2.0%_100%_1		Weight (g)	3819.1	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	201	200	200	167.7	56.871
Diameter (mm)	100	100	100	100	0
X-Section area (mm^2)	7854				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	93.15	10.06	103.40	529.01	176.09	269.42	345.75
1	18.60	2.04	20.70	164.69	112.93	95.33	195.08
2	37.30	4.00	20.68	287.12	129.91	162.92	228.95
3	55.94	6.11	20.70	381.66	146.57	210.43	265.83
4	30.95	3.50	34.50	235.20	131.58	131.15	235.96
5	61.95	6.84	34.49	397.31	155.93	215.61	287.34
6	93.11	10.18	34.48	540.29	172.33	292.63	318.18
7	62.01	6.79	68.88	382.72	162.03	203.05	305.41
8	124.04	13.79	68.88	654.92	189.40	340.98	363.78
9	185.98	20.58	68.89	873.72	212.86	438.91	423.73
10	62.32	6.55	103.39	400.41	155.63	211.35	294.84
11	93.27	10.03	103.40	535.44	174.19	278.00	335.49
12	186.16	20.52	103.39	845.57	220.15	413.75	449.93
13	93.61	9.77	137.90	527.39	177.51	269.92	346.82
14	124.47	13.35	137.90	626.26	198.75	313.43	397.11
15	248.24	27.43	137.90	1032.65	240.39	481.13	515.96

Table B-26 Test Result of Gradation G2, 100% Compaction, 2.0% Moisture Content, Replicate 2

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	20/2/2013 10:37:48				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G2_Water2.0%_100%_2		Weight (g)	3716.4	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	198	199	200	199	1
Diameter (mm)	100	101	102	101	1
X-Section area (mm^2)	8011.8				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	93.02	10.37	103.38	477.30	124.91	104.56	290.30
1	18.60	2.07	20.69	148.92	141.97	182.99	177.90
2	37.27	4.12	20.69	262.50	160.62	242.43	203.65
3	55.72	6.25	20.69	346.90	142.55	150.35	229.84
4	30.91	3.50	34.50	216.86	170.50	248.16	205.61
5	61.93	6.93	34.49	363.26	192.13	324.30	249.57
6	93.00	10.36	34.49	484.05	173.08	242.79	286.78
7	61.85	6.96	68.89	357.31	213.02	379.95	254.72
8	124.01	13.84	68.88	582.15	244.84	468.35	326.39
9	186.26	20.42	68.88	760.75	175.76	240.02	397.70
10	61.83	6.83	103.40	351.81	195.21	318.50	257.61
11	92.88	10.34	103.39	475.81	252.92	443.21	291.62
12	186.25	20.43	103.37	736.37	201.49	303.94	420.22
13	93.05	10.24	137.89	461.80	224.15	353.64	306.14
14	123.92	13.93	137.89	552.83	279.22	508.82	350.41
15							

Table B-27 Test Result of Gradation G2, 100% Compaction, 2.0% Moisture Content, Replicate 3

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	20/2/2013 11:57:09				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G2_Water2.0%_100%_3		Weight (g)	3882.0	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	204.5	204	205.2	204.6	0.603
Diameter (mm)	100	100.1	100	100	0.058
X-Section area (mm^2)	7859.2				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	93.16	10.19	103.38	466.17	130.10	102.27	292.03
1	18.49	2.12	20.70	142.10	149.45	181.20	180.75
2	37.24	4.08	20.70	249.21	166.57	238.79	205.55
3	55.89	6.17	20.70	335.53	152.38	143.29	234.06
4	30.95	3.49	34.50	203.11	176.48	244.75	215.99
5	61.91	6.85	34.49	350.80	194.23	330.17	252.94
6	93.20	10.15	34.49	479.82	178.31	241.39	282.27
7	62.03	6.82	68.88	347.86	210.42	398.59	256.96
8	124.23	13.60	68.88	590.37	233.95	518.78	311.66
9	186.32	20.36	68.88	796.42	165.54	268.14	359.16
10	61.99	6.74	103.39	374.48	188.93	344.51	231.19
11	93.17	10.02	103.38	493.15	244.22	482.92	270.44
12	186.35	20.35	103.37	763.03	192.22	335.66	385.88
13	93.28	10.06	137.89	485.31	216.87	378.12	277.91
14	124.25	13.54	137.89	572.91	282.23	511.79	328.59
15							

Table B-28 Test Result of Gradation G2, 100% Compaction, 3.25% Moisture Content, Replicate 1

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	20/2/2013 13:02:58				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G2_Water3.25%_100%_1		Weight (g)	3890.8	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	195.1	195.5	195.5	195.4	0.231
Diameter (mm)	100	100	100	100	0
X-Section area (mm^2)	7854				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	92.94	10.26	103.38	476.75	194.95	312.54	297.38
1	18.50	2.11	20.69	165.67	111.67	113.54	162.94
2	37.34	3.99	20.69	273.37	136.61	187.91	198.73
3	55.92	6.09	20.69	352.26	158.74	239.62	233.36
4	31.04	3.43	34.50	232.79	133.35	159.99	194.03
5	62.09	6.77	34.49	371.67	167.05	249.47	248.87
6	93.12	10.21	34.49	502.54	185.31	338.29	275.28
7	61.98	6.87	68.89	363.69	170.42	244.32	253.67
8	124.01	13.74	68.89	597.99	207.37	396.99	312.37
9	185.83	20.87	68.89	806.71	230.36	521.61	356.27
10	61.96	6.92	103.39	369.62	167.63	254.73	243.22
11	93.00	10.29	103.38	492.18	188.95	332.90	279.35
12	186.05	20.81	103.39	802.89	231.72	514.82	361.38
13	92.97	10.34	137.89	501.12	185.53	342.41	271.52
14	124.04	13.81	137.89	592.70	209.28	391.18	317.10
15	248.38	27.35	137.89	994.09	249.86	599.52	414.30

Table B-29 Test Result of Gradation G2, 100% Compaction, 3.25% Moisture Content, Replicate 2

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	20/2/2013 14:15:46				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G2_Water3.25%_100%_2		Weight (g)	3970.7	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	201.5	201.5	202	201.7	0.289
Diameter (mm)	100	100	100	100	0
X-Section area (mm^2)	7854				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (μstrain)	Actuator MR (MPa)	Axial resilient (μstrain)	Axial MR (MPa)
0	93.34	10.02	103.39	508.88	183.43	355.55	262.53
1	18.65	2.02	20.70	177.01	105.38	132.12	141.19
2	37.27	4.03	20.69	284.83	130.85	209.96	177.51
3	55.91	6.07	20.69	370.36	150.95	268.09	208.53
4	31.00	3.44	34.50	255.39	121.36	191.49	161.86
5	62.11	6.76	34.49	395.28	157.13	284.86	218.03
6	93.20	10.09	34.50	516.42	180.48	366.81	254.10
7	62.09	6.76	68.90	401.45	154.66	296.42	209.46
8	124.28	13.52	68.89	615.02	202.07	420.91	295.26
9	186.40	20.27	68.89	819.00	227.59	539.29	345.64
10	62.29	6.62	103.40	414.87	150.15	312.14	199.57
11	93.29	10.00	103.38	528.11	176.65	383.57	243.22
12	185.85	20.81	103.37	822.34	226.00	544.19	341.52
13	93.32	9.96	137.89	536.74	173.86	393.33	237.25
14	124.32	13.37	137.89	624.25	199.15	435.64	285.37
15	245.78	29.81	137.88	1101.89	223.06	735.63	334.12

Table B-30 Test Result of Gradation G2, 100% Compaction, 3.25% Moisture Content, Replicate 3

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	20/2/2013 15:30:55				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G2_Water3.25%_100%_3		Weight (g)	3891.0	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	196.5	197	197.5	197	0.5
Diameter (mm)	100	100	100	100	0
X-Section area (mm^2)	7854				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	93.31	10.07	103.39	439.28	212.42	275.90	338.21
1	18.76	1.96	20.70	131.11	143.06	86.50	216.84
2	37.53	3.94	20.70	238.41	157.43	162.31	231.23
3	55.95	6.08	20.70	326.62	171.30	219.82	254.52
4	30.98	3.52	34.50	194.30	159.46	127.68	242.65
5	62.07	6.77	34.50	341.53	181.75	225.25	275.57
6	93.08	10.19	34.49	463.66	200.74	303.71	306.46
7	62.01	6.79	68.90	325.50	190.50	209.47	296.02
8	123.99	13.70	68.90	553.62	223.96	341.25	363.33
9	186.00	20.64	68.90	735.74	252.81	419.36	443.54
10	62.01	6.73	103.39	301.82	205.44	185.12	334.96
11	93.03	10.17	103.39	420.16	221.41	252.72	368.10
12	185.98	20.66	103.40	708.84	262.37	396.90	468.57
13	93.15	10.12	137.89	412.27	225.93	244.42	381.09
14	124.19	13.57	137.89	512.86	242.14	293.60	422.97
15	248.12	27.57	137.89	913.49	271.62	488.44	507.99

Table B-31 Test Result of Gradation G2, 100% Compaction, 4.4% Moisture Content, Replicate 1

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	25/1/2013 11:17:56				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G2_Water4.4%_100%_1		Weight (g)	3891.2	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	199.3	198	199.2	198.8	0.7
Diameter (mm)	100	100	100.2	100.0	0.1
X-Section area (mm^2)	7861.8				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	92.90	10.37	103.39	705.30	131.72	534.60	173.78
1	18.61	2.00	20.70	222.69	83.55	171.59	108.42
2	36.91	4.38	20.70	358.77	102.87	274.63	134.40
3	55.40	6.60	20.69	476.54	116.26	358.48	154.55
4	30.63	3.75	34.49	324.05	94.53	251.13	121.97
5	61.88	7.02	34.50	506.02	122.28	380.77	162.51
6	93.40	9.92	34.49	635.29	147.01	465.90	200.47
7	61.94	6.77	68.90	539.05	114.91	404.46	153.14
8	124.28	13.37	68.89	750.54	165.59	530.28	234.38
9	186.00	20.64	68.90	959.23	193.91	643.85	288.90
10	62.05	6.69	103.39	586.91	105.73	447.18	138.77
11	93.11	10.13	103.39	629.86	147.83	450.13	206.86
12	186.00	20.71	103.39	946.71	196.47	644.31	288.69
13	93.45	9.84	137.88	639.87	146.04	470.04	198.81
14	124.64	13.27	137.88	706.75	176.36	491.35	253.67
15	248.56	27.01	137.89	1172.35	212.02	454.43	546.99

Table B-32 Test Result of Gradation G2, 100% Compaction, 4.4% Moisture Content, Replicate 2

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	25/1/2013 12:33:36				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G2_Water4.4%_100%_2		Weight (g)	3913.0	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	196.6	197.7	198.3	197.5	0.84
Diameter (mm)	100.1	100	100.2	100.1	0.076
X-Section area (mm^2)	7867.1				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				

Modulus test Mean and Std. Deviation data:

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (μstrain)	Actuator MR (MPa)	Axial resilient (μstrain)	Axial MR (MPa)
0	93.35	9.98	103.38	592.37	157.60	434.93	214.64
1	18.64	1.95	20.70	213.01	87.49	166.54	111.90
2	37.27	3.97	20.70	332.71	112.01	258.40	144.22
3	55.86	6.12	20.70	432.83	129.06	329.11	169.74
4	30.98	3.46	34.50	290.63	106.59	224.61	137.92
5	62.17	6.70	34.49	457.86	135.78	346.25	179.55
6	93.51	9.89	34.49	620.96	150.59	467.19	200.16
7	62.11	6.66	68.89	476.46	130.36	368.93	168.36
8	124.41	13.53	68.89	809.93	153.60	611.76	203.36
9							
10							
11							
12							
13							
14							
15							

Table B-33 Test Result of Gradation G2, 100% Compaction, 4.4% Moisture Content, Replicate 3

UTS009 1.32b (27/10/2011) Unbound Material Resilient Modulus and Shear Test					
Date	25/1/2013 13:43:43				
Project	Thesis				
Operator	chanpheng				
Specimen Information:					
Identification	G2_Water4.4%_100%_3		Weight (g)	3901.8	
Dimensions	Point 1	Point 2	Point 3	Average	Std Dev
Length (mm)	198.9	197.7	198.7	198.4	0.7
Diameter (mm)	100	100	99.5	99.8	0.3
X-Section area (mm^2)	7822.6				
Loading program	100				
Load duration (ms)	1000				
Cycle duration (ms)	20				
Conditioning cycle count	20				
Cycles per sequence	200				
Axial Lvdt gauge length (mm)	100				
Modulus test Mean and Std. Deviation data:					

Sequence	Cyclic axial stress (kPa)	Contact stress (kPa)	Confine stress (kPa)	Actuator resilient (µstrain)	Actuator MR (MPa)	Axial resilient (µstrain)	Axial MR (MPa)
0	93.19	10.14	103.38	588.40	158.38	430.86	216.29
1	18.53	2.06	20.69	203.71	90.96	164.22	112.83
2	37.29	4.09	20.70	330.30	112.88	256.32	145.46
3	55.80	6.29	20.69	426.72	130.76	322.49	173.02
4	30.97	3.50	34.49	291.44	106.28	227.09	136.39
5	62.41	6.60	34.50	451.03	138.37	335.31	186.12
6	92.84	10.56	34.49	616.43	150.61	449.29	206.64
7	62.14	6.74	68.89	479.76	129.52	363.08	171.15
8	123.33	14.54	68.89	793.16	155.50	585.49	210.65
9	185.79	20.95	68.89	1007.61	184.39	695.67	267.07
10	62.15	6.72	103.39	546.64	113.70	431.73	143.96
11	92.70	10.72	103.38	692.00	133.96	513.93	180.38
12	185.44	21.22	103.39	1018.41	182.09	677.01	273.92
13	92.81	10.59	137.89	754.47	123.02	557.15	166.59
14	123.32	14.56	137.88	832.42	148.14	583.36	211.39
15	246.32	29.37	137.89	1252.42	196.68	812.37	303.21

Appendix C

Verification of the test data with known relationship

Based on the equation C-1, the possible relationship between Mr and the stress parameters is suggested. The constants $k_1 k_2$ k_3 in the equation can be determined by fitting the equation to the data obtained from a resilient modulus test. The results of determining k constants of each individual Mr test are presented along with adjusted R^2 values in Table C-1

$$M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{\mathrm{oct}}}{P_a} + 1\right)^{k_3} \qquad \text{(Eq. C-1)}$$

$$lnM_r = \ln[k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{\mathrm{OCT}}}{P_a} + 1\right)^{k_3}]$$

$$\ln(\frac{Mr}{P_a}) = \ln k_1 + k_2 \ln\left(\frac{\theta}{P_a}\right) + k_3 \ln\left(\frac{\tau_{\mathrm{OCT}}}{P_a} + 1\right)$$

Follow this equation form;

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2$$

Thus;

$$k_1 = e^{\beta_0},\ k_2 = \beta_1,\ k_3 = \beta_2$$

Where

Mr = resilient modulus. Psi

θ = bulk stress $= \sigma_1 + \sigma_2 + \sigma_3$

σ_1 = major principal stress

σ_2 = intermediate principal stress

σ_2 = σ_3 for Mr test on cylindrical specimen

σ_3 = minor principal stress/confining pressure

τ_{OCT} = octahedral shear stress

$= \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}$

P_a = normalizing stress; atmospheric pressure (101.3kPa)

k_1, k_2, k_3 = regression constants

Table C-1 Results of determining k constants of UGM samples

Sample no.	gradation	%w	%compaction	replicate no.	k1	k2	k3	R^2 adj
CR_G1_2.0_97_1MR	1	2.0	97	1	1.124 *t=0.985* *sig=0.358*	0.578 *t=2.650* *Sig=0.029*	1.143 *t=1.883* *sig=0.104*	*0.886* *sig=0.000*
CR_G1_2.0_97_2MR	1	2.0	97	2	1.510 *t=1.384* *sig=0.216*	-0.034 *t=-0.069* *sig=0.947*	1.406 *t=0.866* *sig=0.420*	*0.179* *sig=0.234*
CR_G1_2.0_97_3MR	1	2.0	97	3	1.229 *t=4.004* *sig=0.004*	*0.061* *t=0.977* *sig=0.35)*	1.178 *t=4.574* *sig=0.002*	0.921 *sig=0.000*
CR_G1_2.0_97_4MR	1	2.0	97	4	2.079 *t=21.174* *sig=0.000*	0.124 *t=2.849* *sig=0.015*	0.788 *t=5.653* *sig=000*	0.937 *sig=0.000*
CR_G1_3.25_97_1MR	1	3.25	97	1	1.330 *t=10.995* *sig=000*	0.375 *t=10.144* *sig=000*	0.377 *t=3.232* *sig=000*	0.984 *sig=0.000*
CR_G1_3.25_97_2MR	1	3.25	97	2	1.115 *t=6.674* *sig=0.000*	0.340 *t=16.548* *sig=0.000*	0.821 *t=12.444* *sig=0.000*	0.994 *sig=0.000*
CR_G1_3.25_97_3MR	1	3.25	97	3	1.289 *t=22.515* *sig=0.000*	0.247 *t=17.399* *sig=0.000*	0.816 *t=17.905* *sig=0.000*	0.996 *sig=0.000*
CR_G1_3.25_97_4MR	1	3.25	97	4	1.486 *t=20.629* *sig=0.000*	0.083 *t=3.355* *sig=0.000*	1.208 *t=15.596* *sig=0.000*	0.987 *sig=0.000*
CR_G1_3.25_97_5MR	1	3.25	97	5	1.387 *t=12.295* *sig=0.000*	0.140 *t=4.180* *sig=0.001*	1.065 *t=9.927* *sig=0.000*	0.977 *sig=0.000*

Sample no.	gradation	%w	%compaction	replicate no.	k1	k2	k3	R^2 adj
CR_G1_4.5_97_2MR	1	4.5	97	1	0.857 *t=-2.891* *sig=0.063*	0.089 *t=0.836* *sig=0.464*	1.473 *t=4.447* *sig=0.021*	0.961 *sig=0.004*
CR_G1_4.5_97_3MR	1	4.5	97	2	1.079 *t=-2.597* *sig=0.063*	0.067 *t=-2.891* *sig=0.063*	1.564 *t=-2.891* *sig=0.063*	0.988 *sig=0.063*
CR_G1_4.5_97_4MR	1	4.5	97	3	1.210 *t=6.058* *sig=0.000*	0.058 *t=1.461* *sig=0.170*	1.253 *t=9835* *sig=0.000*	0.965 *sig=0.000*
CR_G1_5.5_97_1MR	1	5.5	97	1	0.881 *t=-.6.656* *sig=0.022*	0.094 *t=1.707* *sig=0.230*	1.808 *t=8.960* *sig=0.012*	0.986 *sig=0.007*
CR_G1_5.5_97_2MR	1	5.5	97	2	0.791 *t=-7.741* *sig=0.016*	0.009 *t=0.135* *sig=0.905*	1.682 *t=6.297* *sig=0.024*	0.981 *sig=0.009*
CR_G1_2.0_103_1MR	1	2.0	103	1	1.972 *t=38.691* *sig=0.000*	0.193 *t=8.772* *sig=0.000*	0.528 *t=7.457* *sig=0.000*	0.982 *sig=0.000*
CR_G1_2.0_103_2MR	1	2.0	103	2	1.852 *t=17.885* *sig=0.000*	0.196 *t=4.930* *sig=0.000*	1.193 *t=8.296* *sig=0.000*	0.972 *sig=0.000*
CR_G1_3.25_103_2MR	1	3.25	103	1	1.618 *t=23.579* *sig=0.000*	0.358 *t=13.949* *sig=0.000*	0.578 *t=7.016* *sig=0.000*	0.989 *sig=0.000*
CR_G1_3.25_103_3MR	1	3.25	103	2	2.106 *t=12.891* *sig=0.000*	0.253 *t=5.468* *sig=0.000)*	0.868 *t=5.838* *sig=0.000*	0.963 *sig=0.000*
CR_G1_4.5_103_1MR	1	4.5	103	3	1.053 *t=0.677* *sig=0.512*	0.211 *t=2.479* *sig=0.031*	1.300 *t=3.667* *sig=0.004*	0.900 *sig=0.000*

Sample no.	gradation	%w	%compaction	replicate no.	k1	k2	k3	R^2 adj
CR_G1_4.5_103_2MR	1	4.5	103	1	1.415 *t=16.913* *sig=0.000*	0.050 *t=1.940* *sig=0.076*	1.163 *t=14.043* *sig=0.000*	0.982 *sig=0.000*
CR_G1_4.5_103_3MR	1	4.5	103	2	1.361 *t=14.302* *sig=0.000*	0.118 *t=4.379* *sig=0.001*	1.097 *t=12.638* *sig=0.000*	0.984 *sig=0.000*
CR_G1_5.5_103_1MR	1	5.5	103	3	1.122 *t=3.983* *sig=0.003*	0.034 *t=0.799* *sig=0.443*	1.311 *t=7.798* *sig=0.000*	0.939 *sig=0.000*
CR_G1_5.5_103_2MR	1	5.5	103	1	1.324 *t=8.995* *sig=0.000*	0.018 *t=0.366* *sig=0.729*	1.258 *t=7.089* *sig=0.001*	0.970 *sig=0.000*
CR_G1_5.5_103_3MR	1	5.5	103	2	1.121 *t=2.236* *sig=0.056*	-0.003 *t=-0.047* *sig=0.963*	1.105 *t=4.842* *sig=0.001*	*0.853* *sig=0.000*
CR_G2_2.0_100_1MR	2	2.0	100	1	1.970 *t=32.834* *sig=0.000*	0.143 *t=5.503* *sig=0.000*	0.851 *t=10.205* *sig=0.000*	0.981 *sig=0.000*
CR_G2_2.0_100_2MR	2	2.0	100	2	1.677 *t=42.795* *sig=0.000*	0.102 *t=6.691* *sig=0.000*	1.071 *t=21.960* *sig=0.000*	0.994 *sig=0.000*
CR_G2_2.0_100_3MR	2	2.0	100	3	1.699 *t=20.592* *sig=0.000*	0.025 *t=0.759* *sig=0.462*	1.150 *t=11.063* *sig=0.000*	0.969 *sig=0.000*
CR_G2_3.25_100_1MR	2	3.25	100	1	1.680 *t=17.225* *sig=0.000*	0.087 *t=2.303* *sig=0.040*	0.931 *t=7.654* *sig=0.000*	0.954 *sig=0.000*
CR_G2_3.25_100_2MR	2	3.25	100	2	1.435 *t=7.577* *sig=0.000*	0.036 *t=0.599* *sig=0.000*	1.145 *t=5.949* *sig=0.000*	0.903 *sig=0.000*

Sample no.	gradation	%w	%compaction	replicate no.	k1	k2	k3	R^2 adj
CR_G2_3.25_100_3MR	2	3.25	100	3	2.056 *t=49.254* *sig=0.000*	0.226 *t=12.259* *sig=0.000*	0.606 *t=10.248* *sig=0.000*	0.991 *sig=0.000*
CR_G2_4.4_100_1MR	2	4.4	100	1	0.962 *t=-0.898* *sig=0.388*	0.016 *t=0.315* *sig=0.759*	1.677 *t=9.307* *sig=0.000*	0.952 *sig=0.000*
CR_G2_4.4_100_2MR	2	4.4	100	2	1.039 *t=0.413* *sig=0.707*	0.112 *t=0.602* *sig=0.590*	1.584 *t=2.754* *sig=0.071*	0.906 *sig=0.000*
CR_G2_4.4_100_3MR	2	4.4	100	3	1.096 *t=1.550* *sig=0.160*	-0.087 *t=-1.148* *sig=0.284*	1.577 *t=5.922* *sig=0.000*	*0.866* *sig=0.000*

The NCHRP's guide for Mechanistic – Empirical Design refer that usable result from statistical analysis must have adjusted R^2 exceed 0.90. From table C-1, these following samples must reject for the next calculation part:

- CR_G1_2.0_97_1MR adjusted R^2 = 0.886
- CR_G1_2.0_97_2MR adjusted R^2 = 0.179
- CR_G1_5.5_103_3MR adjusted R^2 = 0.853
- CR_G2_4.4_100_3MR adjusted R^2 = 0.866

Biography

Chanpheng Phommavone was born in Xiengkhouang Province, Lao P.D.R, on January 21st, 1985. He graduates the high school level at Phonsavanh high school, Xiengkhouang Province. He graduates in bachelor degree of Communication and Transportation Engineering, Faculty of Engineering, National University of Laos in 2010. After graduates, he continues to studying in the Master of Civil Engineering in Transportation Engineering Division, Department of Civil Engineering, Chulalongkorn University, Thailand, under the AUN/SEED-Net scholarship program.